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Demonstration of Resistive Heating Treatment of DNAPL Source Zone at Launch Complex 34 in Cape Canaveral Air Force Station, Florida

Final Innovative Technology Evaluation Report

by

Battelle
forColumbus, OH 43201

for

The Interagency DNAPL Consortium:

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Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development (ORD) to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

Executive Summary

Dense, nonaqueous-phase liquid (DNAPL) contaminants are a challenge to characterize and remediate at many sites where such contaminants have entered the aquifer due to past use or disposal practices. Chlorinated solvents, comprised of chlorinated volatile organic compounds (CVOCs), such as trichloroethylene (TCE) and perchloroethylene (PCE), are common DNAPL contaminants at sites where operations, such as aircraft maintenance, dry cleaning, metal finishing, and electronics manufacturing have historically occurred. In the past, because of the difficulty in identifying the DNAPL source zone, most remediation efforts focused on controlling the migration of the dissolved CVOC plume. In recent years, many site owners have had success in locating DNAPL sources. DNAPL source remediation is beneficial because once the source has been significantly mitigated, the strength and duration of the resulting plume can potentially be lowered in the long term, and sometimes in the short term as well.

The Interagency DNAPL Consortium

The Interagency DNAPL Consortium (IDC) was formally established in 1999 by the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (U.S. EPA), Department of Defense (DoD), and National Aeronautics and Space Administration (NASA) as a vehicle for marshalling the resources required to test innovative technologies that promise technical and economic advantages in DNAPL remediation. The IDC is advised by a Technical Advisory Group comprised of experts drawn from academia, industry, and government. The IDC and other supporting organizations facilitate technology transfer to site owners/managers though dissemination of the demonstration plans and results, presentations at public forums, a website, and visitor days at the site.

Demonstration Site and Technology

In 1998, after preliminary site characterization conducted by Westinghouse Savannah River Company indicated the presence of a sizable DNAPL source at Launch Complex 34 in Cape Canaveral, Florida, the IDC selected this site for demonstrating three DNAPL remediation technologies. The surficial aquifer at this site lies approximately between 5 and 45 ft below ground surface (bgs). This aquifer can be subdivided into three stratigraphic units —the Upper Sand Unit, the Middle Fine-Grained Unit, and the Lower Sand Unit. Although the Middle Fine-Grained Unit is a conspicuous hydraulic barrier, a Lower Clay Unit underlying the surficial aquifer is considered to be the aquitard that contains the DNAPL source. The Lower Clay Unit appears to be pervasive throughout the demonstration area, although the effective thickness for the unit is only up to 3 ft. The hydraulic gradient in the surficial aquifer is relatively flat. The native aquifer contains relatively high levels of chloride and total dissolved solids (TDS).

The source zone was divided into three test plots, each 75 ft × 50 ft in size, for testing three technologies — in situ chemical oxidation (ISCO), resistive heating, and steam injection. About 15 ft of each plot was under the Engineering Support Building. ISCO and resistive heating were tested concurrently between September 1999 and April/July 2000 in the two outer plots, separated by about 80 ft. Steam injection will be tested in the middle plot, beginning June 2001. The IDC contracted MSE Technology Applications, Inc., to conduct the vendor selection and subcontracting for the three technologies, as well as to track the costs of the demonstration. Current Environmental Solutions (CES) was the vendor selected for implementing resistive heating at Launch Complex 34. Resistive heating was selected because it has the potential to heat the aquifer and remove DNAPL.

Performance Assessment

The IDC contracted Battelle in 1998 to plan and conduct the technical and economic performance assessment of the three technologies. The EPA Superfund Innovative Technology Evaluation (SITE) Program and its contractor TetraTech EM, Inc., provided Quality Assurance (QA) oversight and field support for the performance assessment. Before the ISCO field application, Battelle prepared a Quality Assurance Project Plan (QAPP) or test plan that was reviewed by all the project stakeholders.

This report describes the results of the performance assessment of the resistive heating technology. The objectives of the performance assessment were:

- Estimating change in TCE-DNAPL mass.
- Evaluating changes in aquifer quality.
- Evaluating the fate of the TCE-DNAPL removed from the resistive heating plot.
- Verifying resistive heating operating requirements and costs.

Estimating the TCE-DNAPL mass removal due to the resistive heating application was the primary objective of the demonstration in terms of resources expended for planning, data gathering, and interpretation; the other three were secondary, but important, objectives.

In February 1999, Battelle conducted the preliminary characterization of the DNAPL source region on the north side of the Engineering Support Building (ESB). This characterization provided preliminary DNAPL mass estimates and aquifer data to support the vendor's design of the technology application. It also provided data on the spatial variability of the TCE-DNAPL that supported the design of a more detailed characterization of each test plot before the demonstration. In June 1999, a detailed pre-demonstration characterization of the resistive heating plot was conducted to initiate the performance assessment of the resistive heating technology. From September 1999 to July 2000, when the resistive heating field application was conducted, Battelle collected subsurface data to monitor the progress of the demonstration; the vendor collected additional aboveground data to aid in the operation of the technology. In August-December 2000, the post-demonstration assessment of the resistive heating plot was conducted after all parts of the aquifer had cooled to 90°C or less.

Change in TCE-DNAPL Mass

Detailed soil sampling was used as the main tool for determining changes in TCE-DNAPL mass in the test plot. The spatial distribution data from the preliminary characterization were used to determine a statistically significant number and location of soil samples required to obtain good coverage of the resistive heating plot. A systematic unaligned sampling scheme was used to conduct pre- and post-demonstration soil coring at 12 locations in a 4 × 3 grid in the test plot. Continuous soil samples were collected at every 2-ft vertical interval in each core, resulting in nearly 300 soil samples in the resistive heating plot during each event. A vertical section (approximately 200 g of wet soil) from each 2-ft interval was collected and extracted with methanol in the field; the methanol extract was sent to a certified laboratory for analysis. In this manner, the entire soil column was analyzed from ground surface to aquitard, at each coring location. Pre-demonstration evaluation of this extraction method with Launch Complex 34 soil showed between 72 and 86% decrease in TCE mass in the test plot. Steps were taken during the post-demonstration soil sampling to cool the retrieved cores and to minimize volatilization losses from the hot soil.

The TCE concentrations (mg/kg of dry soil) obtained by this method were considered "total TCE." The portion of the total TCE that exceeded a threshold concentration of 300 mg/kg was considered "DNAPL." This threshold was determined as the maximum TCE concentration in the dissolved and adsorbed phases in the Launch Complex 34 soil; any TCE concentration exceeding this threshold would be DNAPL.

The results of the TCE-DNAPL mass estimation by soil sampling show the following:

- Contouring or linear interpolation of TCE concentrations between sampled points indicated that there was 11,313 kg of total TCE in the resistive heating plot before the demonstration; approximately 10,490 kg of this TCE mass was DNAPL. The total TCE mass in the plot decreased by approximately 90% and the DNAPL mass in the plot decreased by approximately 97% due to the resistive heating application. This predicted decrease in DNAPL mass exceeds the 90% DNAPL removal target proposed at the beginning of the demonstration.
- A statistical evaluation of the pre- and post-demonstration TCE concentrations confirmed these results. Kriging, a geostatistical tool that takes the spatial variability of the TCE distribution into account, indicated that between 7,498 and 15,677 kg of total TCE was present in the test plot before the demonstration. Kriging indicated that the total TCE mass in the test plot decreased between 80 and 93% following the technology application. These statistics are significant at the 80% confidence level specified before the demonstration.
- Kriging confirmed that the pre- and post-demonstration TCE mass estimates obtained by contouring were within the statistically acceptable range. The large number of soil samples that were collected did capture the spatial variability of the TCE distribution.
- The greatest change in TCE-DNAPL mass was observed in the Lower Sand Unit, followed by the Middle Fine-Grained Unit. The Upper Sand Unit showed the least removal. This shows that heating was most effective in the deeper portions of the aquifer. Limitations due to the new electrode design used at Launch Complex 34 and the loss of vadose zone encountered during high-rainfall events may have contributed to lower heating/steam stripping efficiency in the shallower regions of the aquifer. The temperature distribution in the test plot determined in May 2000, towards the end of the resistive heating field application, showed relatively good heating in all three aquifer units — Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit.
- Most of the DNAPL present in regions that would be considered difficult to access was removed from the test plot by resistive heating. Considerable DNAPL was removed from the region immediately above the aquitard (Lower Clay Unit) and from under the building.

- The change in TCE-DNAPL mass was relatively high under the building, indicating that these regions could be efficiently accessed by using angled electrodes outside the building. Any remediation of DNAPL from further under the building probably would require electrodes that are installed inside the building.

Changes in Aquifer Quality

Application of the resistive heating technology caused the following changes in the treated aquifer:

- Dissolved TCE levels declined in several monitoring wells in the resistive heating plot, although none of the wells showed post-demonstration concentrations of less than 5 µg/L, the federal drinking water standard, or 3 µg/L, the State of Florida ground-water target cleanup level. *Cis*-1,2-DCE levels remained above 70 µg/L and increased considerably in some wells. Vinyl chloride (1 µg/L State of Florida target) levels could not be accurately determined because higher TCE and *cis*-1,2-DCE levels elevated the detection limits of vinyl chloride. This indicates that, in the *short-term*, removal of DNAPL mass from the targeted aquifer caused ground-water TCE concentrations to decline. Dissolved-phase CVOCs were not as efficiently removed, especially from the upper portions of the aquifer, probably due to the lower heating/stripping efficiency in the shallower regions.
- The TCE degradation product *cis*-1,2-DCE appeared to be accumulating in the ground water in the test plot. *Cis*-1,2-DCE itself is subject to drinking water standards (70 µg/L) and its buildup in the plot could be a concern. Its accumulation in the plot may indicate that the degradation rate of *cis*-1,2-DCE is not as fast as the degradation rate of TCE, under the conditions prevalent in the aquifer.
- Ground-water pH and dissolved oxygen levels remained relatively constant, but chloride, sodium, potassium, sulfate, alkalinity (carbonate), and TDS levels rose sharply. TDS levels were above the secondary drinking water standard of 500 mg/L both before and after the demonstration, classifying the aquifer as brackish. Sources of these dissolved solids could include evaporative residue, saltwater intrusion, displacement of exchangeable sodium from aquifer minerals, migration from the ISCO plot, and/or CVOC degradation.
- Biological oxidation demand and total organic carbon (TOC) levels in the ground water generally increased. These increases could be due to dissolution of humic and fulvic matter in the aquifer under the heat treatment.
- The ground-water levels of iron, chromium, and nickel remained relatively constant. There does not appear to be any significant corrosion of the stainless steel monitoring wells of the kind experienced in the ISCO plot.
- Slug tests conducted in the resistive heating plot before and after the demonstration did not indicate any noticeable changes in the hydraulic conductivity of the aquifer.
- Although difficulties were encountered in operating the drill rig during post-demonstration coring, the geochemical composition of the soil does not appear to have changed much due to the heat treatment. Quartz and aragonite make up the majority of the minerals identified in soil samples from heat-affected and unaffected regions of the aquifer. Aragonite may be associated with the seashell fragments found in fair abundance in the aquifer. Calcite and margarite (mica) are less abundant in the aquifer.

Fate of TCE-DNAPL Mass in the Test Plot

The decrease in TCE-DNAPL mass in the plot could have resulted from one or more of the following pathways:

- Aboveground recovery. Vapor sampling conducted by the resistive heating vendor indicates that 1,947 kg of total TCE was recovered in the vapor extraction system. The initial estimate of total TCE mass in the subsurface was 11,313 kg.
- Degradation by biological or abiotic processes. There are indications that some TCE may have been degraded due to the heating in the resistive heating plot.
    - The sharp increase in *cis*-1,2-DCE levels in several monitoring wells inside the plot and perimeter indicate the possibility that some TCE may have degraded by reductive dechlorination. Microbial counts in soil and groundwater samples before and after the demonstration indicate that microbial populations survived the heat treatment in most parts of the plot. If TCE degradation to *cis*-1,2-DCE has been hastened, it is unclear as to the time frame over which *cis*-1,2-DCE itself may degrade. Accumulation of *cis*-1,2-DCE shows that the rate of degradation of TCE may be much faster than the rate of *cis*-1,2-DCE degradation.
    - The sharp increase in chloride, which would have been a strong indicator of dechlorination of CVOCs, proved to be inconclusive. Sodium, potassium, sulfate, alkalinity, and TDS increased sharply, concomitant with the increase in chloride — these are all seawater constituents. The possibility of the increase in chloride was caused by saltwater intrusion during the resistive heating application. Also, potential vaporization of the water may have resulted in the increased chloride concentrations.
    - Abiotic processes that may have degraded TCE include reductive dechlorination by the steel shot in the electrodes, hydrolysis, and/or oxidation. Any of these processes could have been promoted by the heating in the plot.
- Migration to surrounding regions. There are indications that some TCE, and perhaps DNAPL, may have migrated to regions surrounding the resistive heating plot.
    - Monitoring wells (IW-17S and IW-17I) outside the western perimeter of the plot showed a sustained increase in TCE concentrations during and after the demonstration. TCE was found in transient surface water that appeared along a ditch on the western side of the plot, following the two hurricane events. It is possible that when the water table rose to the ground surface, the vapor extraction piping in the plot was submerged. Hot water laden with TCE could have migrated westward along the topographic gradient. Another possible obstruction to the TCE vapors being extracted through the extraction pipes and plenum in the vadose zone and ground surface is the Middle Fine-Grained Unit. TCE vapors and steam migrating upwards could preferentially migrate horizontally in the sandy layer under the Middle Fine-Grained Unit rather than through the silty layer above. A limited number of exploratory soil cores collected in the regions surrounding the resistive heating plot after the demonstration did not show any signs of fresh DNAPL deposits.
    - DNAPL appeared in two of the wells (PA-2I and PA-2D) on the eastern side of the plot. It is not clear which of the two technologies, ISCO or resistive heating, caused DNAPL to migrate. ISCO in the neighboring test plot (80 ft away) created a strong hydraulic gradient that could potentially

    displace any mobile DNAPL in the aquifer. Resistive heating generates heat-induced convection gradients that could displace mobile DNAPL or mobilize residual DNAPL. On the other hand, the PA-2 well cluster was installed in a region that was showing dissolved TCE levels close to its solubility before the demonstration. It is possible that DNAPL would have eventually appeared in these wells regardless of the neighboring remediation activities.

    - Soil core samples from the vadose zone above the resistive heating-treated aquifer did not show any noticeable increase in TCE concentrations.
    - Surface emission tests conducted inside and around the plot on several occasions during and immediately following the resistive heating application showed noticeably elevated levels of TCE, compared to background levels. This indicated that the vapor capture system was not as efficient as would be desired and some CVOC vapors were migrating to the atmosphere. On some occasions, steam (and probably CVOC vapors) shot out of the monitoring wells for several seconds during sampling. This is another potential route for CVOC vapors.
    - After the resistive heating and ISCO demonstrations, three wells were installed into the confined aquifer – one in the parking lot to the north (PA-20), one in the ISCO plot (PA-21) and one in the resistive heating plot (PA-22). All three wells showed elevated levels of dissolved TCE, but the levels were especially high in PA-22. Ground water in PA-22 also had elevated temperature (44 to 49°C); it is not clear whether the elevation in temperature was caused by conduction or convection. The soil cores collected during the installation of these wells showed the presence of DNAPL in the Lower Clay Unit and confined aquifer below the ISCO plot and below the resistive heating plot, but not under the parking lot, which is outside the suspected DNAPL source zone. TCE concentrations were particularly high in soil and ground-water samples collected from under the resistive heating plot. Because these wells were installed only after the demonstration, it is unclear as to when the DNAPL migrated to the confined aquifer. The resistive heating treatment heated the base of the aquifer and probably the aquitard fairly well and the buoyancy of the water would probably create vertically upward gradients. It is possible that the DNAPL penetrated the aquitard gradually over time, long before the demonstration.
    - The power outage and ground-water recharge resulting from two hurricane events (Floyd, September 10, 1999; and Irene, October 17, 1999) during the operation may have caused some loss of TCE.

- Losses during sampling of hot soil cores. It is possible that some CVOC losses occurred during post-demonstration sampling of the hot (90°C or less) soil cores. This would cause an underestimation of the TCE-DNAPL mass remaining in the resistive heating plot after the demonstration. However, all precautions had been taken to minimize any such losses. By the time the post-demonstration soil sampling was done, the plot had cooled to 90°C or less, indicating that steam generation had subsided. Each time the soil sample barrel was retrieved from the ground, it was immediately capped at both ends and submerged in an ice bath until the core temperature cooled to ambient.

- The monitoring indicates that some TCE may have degraded through one or more of several heat-induced degradation (or accelerated biodegradation) mechanisms. It is also possible that some TCE may have migrated from the resistive heating plot through a variety of possible pathways. It also is possible

> that some of the migrating TCE was DNAPL. The resistive heating application at Launch Complex 34 generated the desired heating in most parts of the plot, even in difficult spots, such as immediately above the aquitard and under the building. Heating in the shallower regions of the plot was somewhat hampered by the deficiencies of the new electrode design and by the transient diminishing of the vadose zone. Vapor capture is the biggest challenge that the technology needs to engineer for in future applications.

In summary, the TCE in the plot probably was dissipated by the resistive heating treatment through a number of possible pathways, including aboveground vapor recovery and condensation, microbial degradation, and migration to the surrounding regions. The possible buildup and persistence of *cis*-1,2-DCE in the plot, as well as dechlorination to ethenes, due to heat-accelerated biodegradation needs to be studied. Ways of maximizing any such biodegradation and minimizing migration outside the plot need to be determined during future resistive heating applications.

At Launch Complex 34, a mechanism (such as a vertical pipe) for channeling upward-migrating CVOC vapors past the Middle Fine-Grained Unit probably would have improved capture. Better hydraulic and pneumatic control, as well as better heating, near the water table, vadose zone, and ground surface would have improved vapor capture. Better design could have increased observed recovery and decreased potentially undesirable losses outside the plot.

Verifying Operating Requirements

The resistive heating heat application began on August 18, 1999 and continued until July 12, 2000, with two major breaks in between. The SVE system was operated for two more months until September 19, 2000 so that continuing vapors from the still-hot aquifer could be recovered. Over the course of the demonstration, a total of 1,725,000 kW-hrs of energy was applied to the subsurface. The applied voltage ranged from 100 to 500 V, which resulted in an electrical current of 10 to 400 amps.

At this site, the vendor used a novel electrode design consisting of an electrical cable attached to a ground rod within a graphite backfill, instead of the traditional pipe electrode. However, this new design, coupled with excessive rainfall and a rising water table, resulted in insufficient heating of the upper part of the aquifer. Therefore, between February 24 and March 2, 2000, the vendor installed ground rods near each electrode to heat the 3- to 10-ft-bgs ground interval.

The first major interruption of the resistive heating operation occurred between September 30 and December 12, 1999. On September 10 a major hurricane (Hurricane Floyd) hit Cape Canaveral, followed by a second hurricane (Hurricane Irene) on October 17, 1999. The power supply was damaged and the water table rose significantly, from about 6 ft bgs before the demonstration to almost 1.5 ft bgs in monitoring well PA-2. In low-lying areas of the test plot, the ground water was probably near the ground surface. Elevated TCE levels discovered in ponded surface water in a ditch along the west side of the resistive heating plot indicate that some TCE migrated from the plot during this period. It is probable that infiltration of cooler rainwater from the storms caused the rising TCE vapors to condense near the ground surface. In addition, the rising water table submerged the SVE wells rendering them useless; it is probable that some TCE volatilized to the atmosphere during this time.

In October 1999, the vendor installed six horizontal wells in the northern half of the cell and seven shallow vertical wells in the southern half of the cell near the building. In addition, a surface cover (plenum) was placed over the plot to improve vapor capture. In October 1999, the vendor also installed a drainage diversion system consisting of a sandbag cutoff wall on the east side of the plot and a sump pump to divert the water through a PVC pipe to the drainage collection area in the west. Also, PVC risers on the six monitoring wells inside the plot were removed and replaced with stainless steel risers. Due to these modifications and the repairs resulting from the hurricanes, the resistive heating system was operated only for six weeks during the first heating cycle. The second heating cycle started on December 12, 1999 and continued for 13 weeks.

On March 24, 2000, operations were interrupted to replace the transformer, a major piece of equipment, whose lease had run out. A replacement transformer was obtained and installed in April, but the third heating cycle could begin only on May 11, 2000 due to an unusually heavy space shuttle launch schedule that necessitated work stoppages. The third heating cycle continued for eight weeks until July 12, 2000, when the IDC determined that VOC extraction rates had declined significantly. The SVE system remained operational until September 19, 2000, by which time subsurface temperatures had fallen below 95°C, indicating that steaming had stopped.

A major concern with the resistive heating technology was the high voltage (up to 500 V) required to be delivered to the subsurface. Despite all the difficulties involving hurricanes and flooding of the plot, the vendor successfully controlled the transport and distribution of the large amounts of electricity involved. At all times, the ground surface was successfully insulated from the electric current running through the aquifer. The ground surface above the resistive heating plot was available for other activities during the voltage applications. This successful management of the high voltage application is probably the most important safety achievement of the demonstration.

The voltage application was turned off whenever monitoring wells were sampled inside the test plot and all sampling events were conducted safely. Because the monitoring well screens were completely submerged under the water table, there was a tendency for steam pressure to build up in the monitoring wells. A pressure gauge and pressure release valve were installed on each monitoring well inside the plot and along the perimeter. System operators and sampling personnel wore Level D personal protective equipment at the site. No injuries were encountered during the demonstration.

Economics

The total cost of the resistive heating application was **$613,000**. The vendor incurred a total cost of approximately $569,000 for resistive heating treatment of the 75-ft x 50-ft x 45-ft test plot at Launch Complex 34. This total includes the design, equipment, mobilization/demobilization and operation costs. In addition, NASA incurred a cost of $44,000 for off-site waste disposal. Aboveground wastes requiring disposal included the condensate (shipped to the on-site wastewater treatment plant), spent carbon (shipped to the supplier for regeneration), and the permanganate-impregnated silica (shipped to a local landfill).

A comparison of the cost of resistive heating treatment of the DNAPL source the size of the resistive heating plot and an equivalent (2 gallon per minute [gpm]) pump-and-treat system for plume control over the next 30 years was conducted to evaluate the long-term economic impact of the technology. The present value (PV) of building and operating a pump-and-treat system for 30 years was estimated as $1,406,000. Assuming that the resistive heating application was effective and displacement did not occur, the resistive heating application cost, therefore, is less than the present value (PV) of a 30-year pump-and-treat application.

This comparison assumes that natural attenuation would be sufficient to address any residual source. Also, in the absence of source treatment, the plume emanating from this relatively large DNAPL source may be expected to last much more than 30 years. Resistive heating treatment and natural attenuation require none of the aboveground structures, recurring operational costs, and maintenance that pump-and-treat systems require. Anecdotal evidence indicates that, at many sites, pump-and-treat systems are operational only about 50% of the time. The impact of this downtime and the associated maintenance costs should also be considered. In general, the economics favor DNAPL source treatment over a pump-and-treat system at this site.

Site characterization costs were not included in the cost comparison because a good design of either a source treatment (e.g., resistive heating) or plume control (e.g., pump and treat) remedial action would require approximately the same degree of characterization. The site characterization conducted by Battelle in February 1999 is typical of the characterization effort that may be required for delineating a 75-ft × 50-ft × 45-ft DNAPL source; the cost of this effort was $255,000, which included a work plan, 12 continuous soil cores to 45 ft bgs, installation of 36 monitoring wells, field sampling, laboratory analysis of samples, field parameter measurements, hydraulic testing, data analysis, and report.

Regulatory and Administrative Considerations

DNAPL source remediation, in general, and resistive heating, in particular, is a treatment option that results in risk reduction through removal of DNAPL from the subsurface. Contaminant volume reduction and, to some extent, toxicity reduction resulted from the TCE extraction and its possible degradation due to the resistive heating treatment. Better hydraulic and pneumatic control, as well as better heating, near the water table, vadose zone, and ground surface would improve vapor capture at future sites.

Although the eventual target for the Launch Complex 34 aquifer is to meet Florida state-mandated ground-water cleanup goals (3 µg/L of TCE, 70 µg/L of *cis*-1,2-DCE, and 1 µg/L of vinyl chloride), the Technical Advisory Group recommended a more feasible and economically viable goal of 90% removal of DNAPL mass. From the experience of the demonstration, it appears that, at least from the site owner's perspective, three types of cleanup goals may be envisioned for source remediation – a short-term goal, an intermediate-term goal, and a long-term goal. At Launch Complex 34, the **short-term goal** of the cleanup was to remove at least 90% of the DNAPL mass, and was the immediate goal given to the technology vendors. Although more than 90% reduction of the DNAPL mass was observed in the resistive heating plot, ground-water concentrations of TCE declined substantially, but not to 3 µg/L. On the other hand, *cis*-1,2-DCE levels increased, as some TCE probably degraded reductively. Although some rebound in TCE concentrations may be expected in the future, it is possible that in the intermediate term (say, a year after the source treatment), a weakened plume will result. Therefore, in the intermediate term, there is a possibility that the source treatment, in conjunction with natural attenuation (or other plume control measure, if necessary), would allow cleanup targets to be met at a downgradient compliance point (e.g., property boundary). With source treatment, meeting ground-water cleanup targets is likely to be an **intermediate-term** goal.

The **long-term goal** of source treatment would be faster dismantling of any interim plume control remedy (natural attenuation or other treatment) that may be implemented to meet ground-water cleanup targets at the compliance point. Faster dismantling of any interim remedy is likely to result from the fact that DNAPL mass removal would hasten the eventual depletion of the TCE source. A possible long-term benefit could also accrue from the fact that source treatment may result in a weakened plume that would require a much lower magnitude of long-term treatment (and cost).

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Acronyms and Abbreviations

ACL	alternative concentration limits
AFRL	Air Force Research Laboratory
ARARs	applicable or relevant and appropriate requirements
bgs	below ground surface
BOD	biological oxygen demand
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CES	Current Environmental Solutions
CVOC	chlorinated volatile organic compound
CWA	Clean Water Act
DCE	*cis*-1,2-dichloroethylene
DNAPL	dense, nonaqueous-phase liquid
DO	dissolved oxygen
DoD	Department of Defense
DOE	Department of Energy
EM50	Environmental Management 50 (Program)
ESB	Engineering Support Building
FDEP	(State of) Florida Department of Environmental Protection
FSU	Florida State University
GAC	granular activated carbon
gpm	gallon(s) per minute
HSWA	Hazardous and Solid Waste Amendments
IDC	Interagency DNAPL Consortium
ISCO	in situ chemical oxidation
ITRC	Interstate Technologies Regulatory Council
JCPDF	Joint Commission on Powder Diffraction Files
LCS	laboratory control spikes
LCSD	laboratory control spike duplicates
LRPCD	Land Remediation and Pollution Control Division
MCL	maximum contaminant level
MS	matrix spikes

MSD	matrix spike duplicates
msl	mean sea level
MSE	MSE Technology Applications, Inc.
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NFESC	Naval Facilities Engineering Service Center
NPDES	National Pollutant Discharge Elimination System
O&M	operation and maintenance
ORD	Office of Research and Development
ORNL	Oak Ridge National Laboratory
ORP	oxidation-reduction potential
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PAH	polycyclic aromatic hydrocarbon
PCE	perchloroethylene
PID	photoionization detector
POTW	publicly owned treatment works
PV	present value
PVC	polyvinyl chloride
QA	quality assurance
QAPP	Quality Assurance Project Plan
QC	quality control
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RI/FS	Remedial Investigation/Feasibility Study
RIR	relative intensity ratio
RPD	relative percent difference
RSKERC	R.S. Kerr Environmental Research Center (of the U.S. EPA)
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
SIP	State Implementation Plans
SITE	Superfund Innovative Technology Evaluation (Program)
STL	STL Environmental Services, Inc.
SVE	soil vapor extraction
TCA	trichloroethane
TCE	trichloroethylene
TDS	total dissolved solids
TOC	total organic carbon
U.S. EPA	United States Environmental Protection Agency
VOA	volatile organic analysis
WSRC	Westinghouse Savannah River Company
XRD	x-ray diffraction

1. Introduction

This section is an introduction to the demonstration of the resistive heating technology for remediation of a dense, nonaqueous-phase liquid (DNAPL) source zone at Launch Complex 34, Cape Canaveral Air Force Station, FL. The section also summarizes the structure of this report.

1.1 Project Background

The goal of the project is to evaluate the technical and cost performance of the resistive heating technology for remediation of DNAPL source zones. Resistive heating was demonstrated at Launch Complex 34, Cape Canaveral Air Force Station, FL, where the chlorinated volatile organic compound (CVOC) trichloroethylene (TCE) is present in the aquifer as a DNAPL source. Smaller amounts of dissolved *cis*-1,2-dichloroethylene (DCE) and vinyl chloride also are present in the ground water. The field application of the technology started in August 1999 and ended in July 2000. Pre- and post-demonstration performance assessment activities were conducted before, during, and after the field demonstration.

1.1.1 The Interagency DNAPL Consortium

The resistive heating demonstration is part of a larger demonstration of three different DNAPL remediation technologies being conducted at Launch Complex 34 with the combined resources of several U.S. government agencies. The government agencies participating in this effort have formed the Interagency DNAPL Consortium (IDC). The IDC is composed primarily of the following agencies, which are providing most of the funding for the demonstration:

- Department of Energy (DOE), Environmental Management 50 (EM50) Program
- U.S. Environmental Protection Agency (U.S. EPA), Superfund Innovative Technology Evaluation (SITE) Program
- Department of Defense (DoD), Naval Facilities Engineering Service Center (NFESC)
- National Aeronautics and Space Administration (NASA).

In the initial stages of the project, until January 2000, the Air Force Research Laboratory (AFRL) was the DoD representative on this consortium and provided significant funding. NFESC replaced AFRL in March 2000. In addition, the following organizations are participating in the demonstration by reviewing project plans and data documents, funding specific tasks, and/or promoting technology transfer:

- Patrick Air Force Base
- U.S. EPA, R.S. Kerr Environmental Research Center (RSKERC)
- Interstate Technologies Regulatory Council (ITRC).

Key representatives of the various agencies constituting the IDC have formed a Core Management Team, which guides the progress of the demonstration. An independent Technical Advisory Group has been formed to advise the Core Management Team on the technical aspects of the site characterization and selection, remediation technology selection and demonstration, and the performance assessment of the technologies. The Technical Advisory Group consists of experts drawn from industry, academia, and government.

The IDC contracted MSE Technology Applications, Inc. (MSE) to conduct technology vendor selection, procure the services of the three selected technology vendors, and conduct the cost evaluation of the three technologies. Current Environmental Solutions (CES) was the selected vendor for implementing the resistive heating technology at Launch Complex 34. IT Corporation and Integrated Water Resources, Inc., were the vendors for the in situ chemical oxidation (ISCO) and steam injection technologies, respectively. In addition, the IDC also contracted Westinghouse Savannah River Company

(WSRC) to conduct the preliminary site characterization for site selection, and Florida State University (FSU) to coordinate site preparation and other field arrangements for the demonstration. Figure 1-1 summarizes the project organization for the IDC demonstration.

1.1.2 Performance Assessment

The IDC contracted Battelle to plan and conduct the detailed site characterization and an independent performance assessment for the demonstration of the three technologies. U.S. EPA and its contractor TetraTech EM, Inc., provided quality assurance (QA) oversight and field support for the performance assessment activities. Before the field demonstration, Battelle prepared a Quality Assurance Project Plan (QAPP) that was reviewed by all the project stakeholders. This QAPP was based on the general guidelines provided by the U.S. EPA's SITE Program for test plan preparation, QA, and data analysis (Battelle, 1999d). Once the demonstration started, Battelle prepared eight interim reports (Battelle 1999e, and f; Battelle 2000a, b, and c; Battelle 2001a, b, and c).

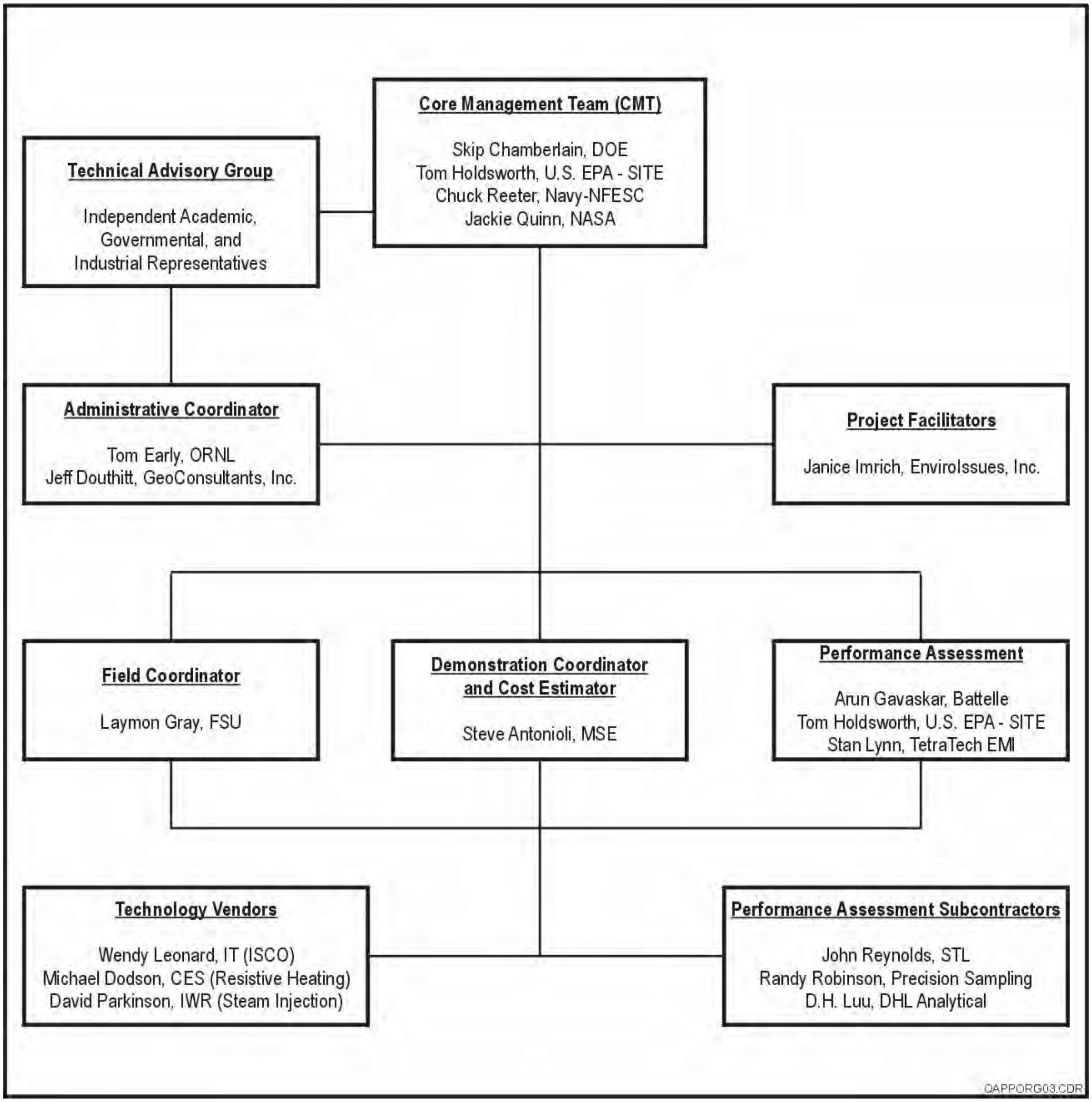

Figure 1-1. Project Organization for the IDC Demonstration at Launch Complex 34

1.1.3 *The SITE Program*

The performance assessment planning, field implementation, and data analysis and reporting for the resistive heating demonstration followed the general guidance provided by the U.S. EPA’s SITE Program. The SITE Program was established by U.S. EPA's Office of Solid Waste and Emergency Response (OSWER) and the Office of Research and Development (ORD) in response to the 1986 Superfund Amendments and Reauthorization Act, which recognized a need for an "Alternative or Innovative Treatment Technology Research and Demonstration Program." ORD’s National Risk Management Research Laboratory in the Land Remediation and Pollution Control Division (LRPCD), headquartered in Cincinnati, OH, administers the SITE Program. The SITE Program encourages the development and implementation of (1) innovative treatment technologies for hazardous waste site remediation and (2) innovative monitoring and measurement tools.

In the SITE Program, a field demonstration is used to gather engineering and cost data on the innovative technology so that potential users can assess the technology's applicability to a particular site. Data collected during the field demonstration are used to assess the performance of the technology, the potential need for pre- and postprocessing of the waste, applicable types of wastes and waste matrices, potential operating problems, and approximate capital and operating costs.

U.S. EPA provides guidelines on the preparation of an Innovative Technology Evaluation Report at the end of the field demonstration. These reports evaluate all available information on the technology and analyze its overall applicability to other site characteristics, waste types, and waste matrices. Testing procedures, performance and cost data, and quality assurance and quality standards are also presented. This IDC report on the resistive heating technology demonstration at Launch Complex 34 is based on these general guidelines.

1.2 The DNAPL Problem

Figure 1-2 illustrates the formation of a DNAPL source at a chlorinated solvent release site. When solvent is released into the ground due to previous use or disposal practices, it travels downward through the vadose zone to the water table. Because many chlorinated solvents are denser than water, the solvent continues its downward migration through the saturated zone (assuming sufficient volume of solvent is involved) until it encounters a low-permeability layer or aquitard, on which it may form a pool. During its downward migration, the solvent leaves a trace of residual solvent in the soil pores. Many chlorinated solvents are only sparingly soluble in water; therefore, they can persist as a separate phase for several years (or decades). This free-phase solvent is called DNAPL.

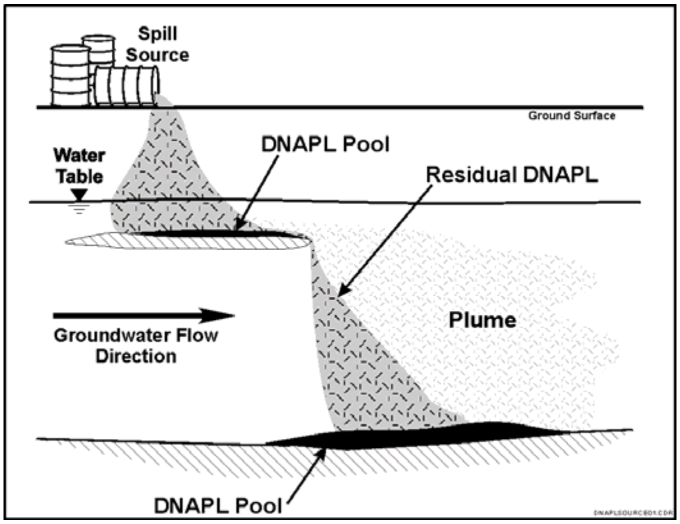

Figure 1-2. Formation of a DNAPL Source in an Aquifer

DNAPL in pools can often be mobilized towards extraction wells when a strong hydraulic gradient is imposed; this solvent is called mobile DNAPL. Residual DNAPL is DNAPL that is trapped in pores and cannot be mobilized towards extraction wells, regardless of how strong the applied gradient. DNAPL pools may dissolve in the ground-water flow over time, leaving behind residual DNAPL. At most sites, DNAPL pools are rare; DNAPL is often present in residual form.

As long as there is DNAPL in the aquifer, a plume of dissolved solvent is generated. DNAPL therefore constitutes a secondary source that keeps replenishing the plume long after the primary source (leaking aboveground or buried drums, drain pipes, vadose zone soil, etc.) has been removed. Because DNAPL persists for many decades or centuries, the resulting plume also persists for many years. As recently as five years ago, DNAPL sources were difficult to find and most remedial approaches focused on plume treatment or plume control. In recent years, many chlorinated solvent-contaminated sites have been successful in identifying DNAPL sources, or at least identifying enough indicators of DNAPL. The focus is now shifting to development and validation of techniques that have potential to affect DNAPL source removal or treatment.

Pump-and-treat systems have been the conventional treatment approach at DNAPL sites and these systems have proved useful as an interim remedy to control the progress of the *plume* beyond a property boundary or other compliance point. However, pump-and-treat systems may not be economical for residual *DNAPL* source remediation. Pools of DNAPL, which can be pumped and treated above ground, are rare. Residual DNAPL is immobile and does not migrate towards extraction wells. As with plume control, the effectiveness and cost of DNAPL remediation with pump and treat is governed by the time (decades) required for slow dissolution of the DNAPL source in the ground-water flow. An innovative approach is required to address the DNAPL problem.

1.3 The Resistive Heating Technology

In the early 1990s, Pacific Northwest National Laboratory developed the resistive heating technology for heat treatment of vadose and saturated zone soils, as well as ground water. It splits conventional three-phase electricity into six electrical phases and delivers it to the subsurface through metal electrodes (see Figure 1-3). In the subsurface, the electrical energy resistively heats the soil and ground water to generate steam. A combination of direct volatilization and steam stripping drives contaminants to the vadose zone, where a vapor extraction system collects the steam and contaminant vapors and treats them in an aboveground treatment system. Typically, a condenser and activated carbon have been used as an aboveground treatment system for the extracted vapors. Thermal processes, such as steam injection and resistive heating, have also been reported as causing in situ degradation of organic contaminants by a variety of processes, such as hydrolysis, oxidation, and enhanced microbial action. Over the years, the resistive heating system has been developed to the point where the ground surface is insulated from the subsurface electrical energy and continued site access is possible to personnel during the application.

1.4 The Demonstration Site

Launch Complex 34, the site selected for this demonstration, is located at Cape Canaveral Air Force Station, FL (see Figure 1-4). Launch Complex 34 was used as a launch site for Saturn rockets from 1960 to 1968. Historical records and worker accounts suggest that rocket engines were cleaned on the launch pad with chlorinated organic solvents such as TCE. Other rocket parts were cleaned on racks at the western portion of the Engineering Support Building and inside the building. Some of the solvents ran off to the surface or discharged into drainage pits. The site was abandoned in 1968 and since that time much of the site has been overgrown by vegetation, although several on-site buildings remain operational.

Preliminary site characterization efforts suggested that approximately 20,600 kg (Battelle, 1999a) to 40,000 kg (Eddy-Dilek et al., 1998) of solvent could be present in the subsurface near the Engineering Support Building at Launch Complex 34. Figure 1-5 is a map of the Launch Complex 34 site at Cape Canaveral depicting the Engineering Support Building and vicinity, where the demonstration was conducted. The DNAPL source zone was large enough that the IDC and the Technical Advisory Group could assign three separate test plots

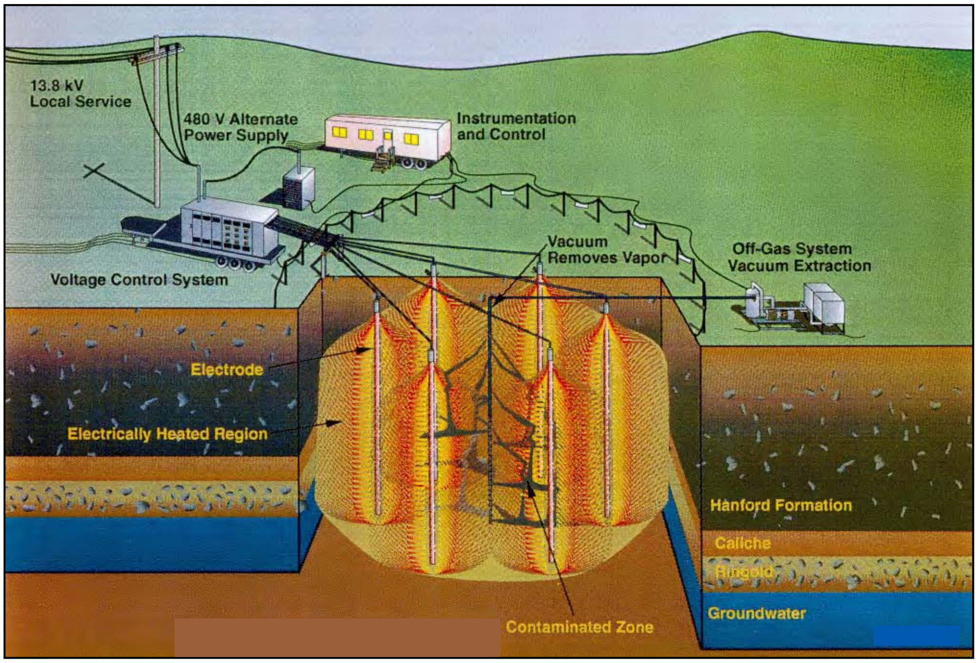

Figure 1-3. Illustration of the Resistive Heating Technology for Subsurface Treatment

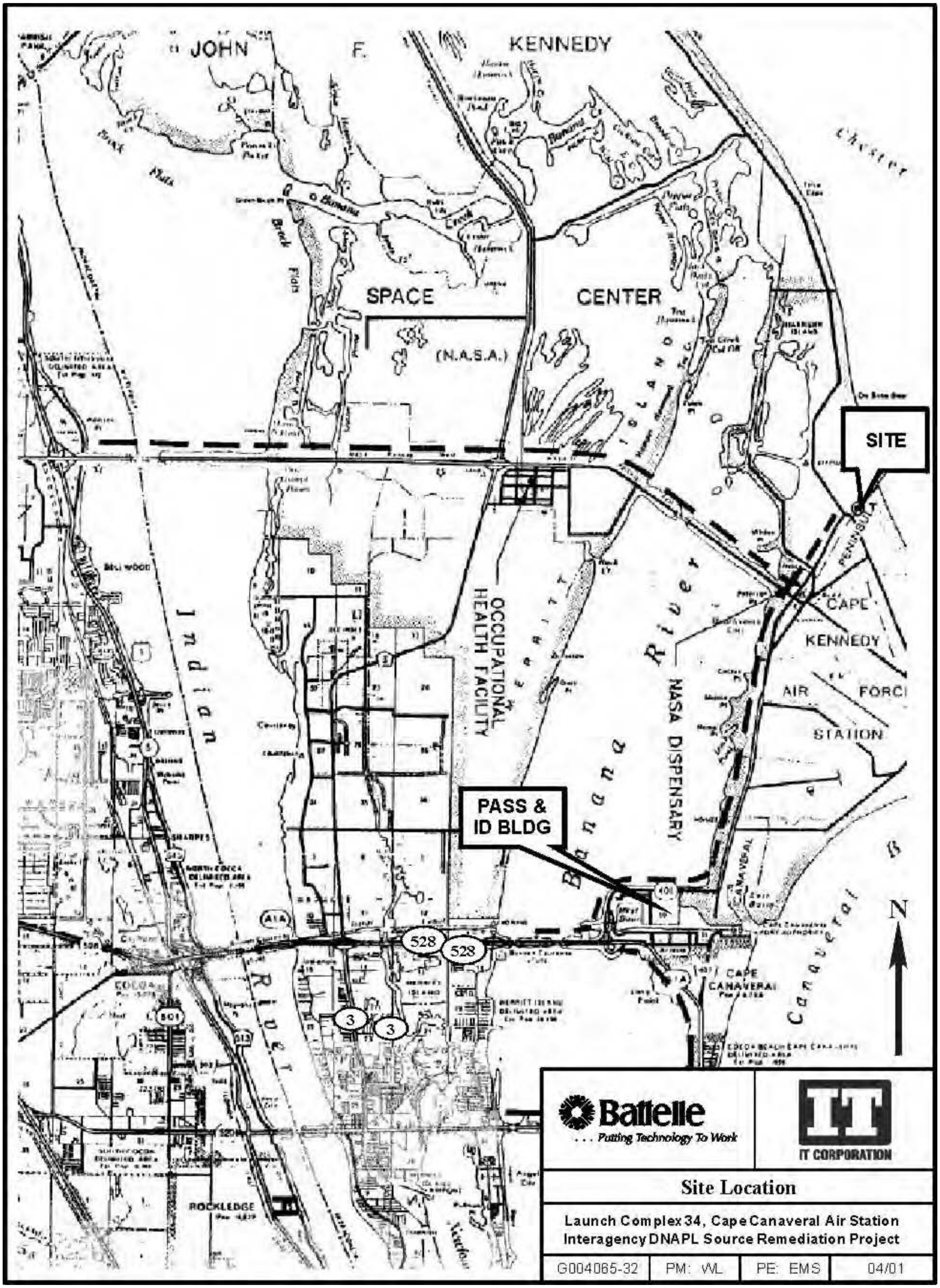

Figure 1-4. Demonstration Site Location

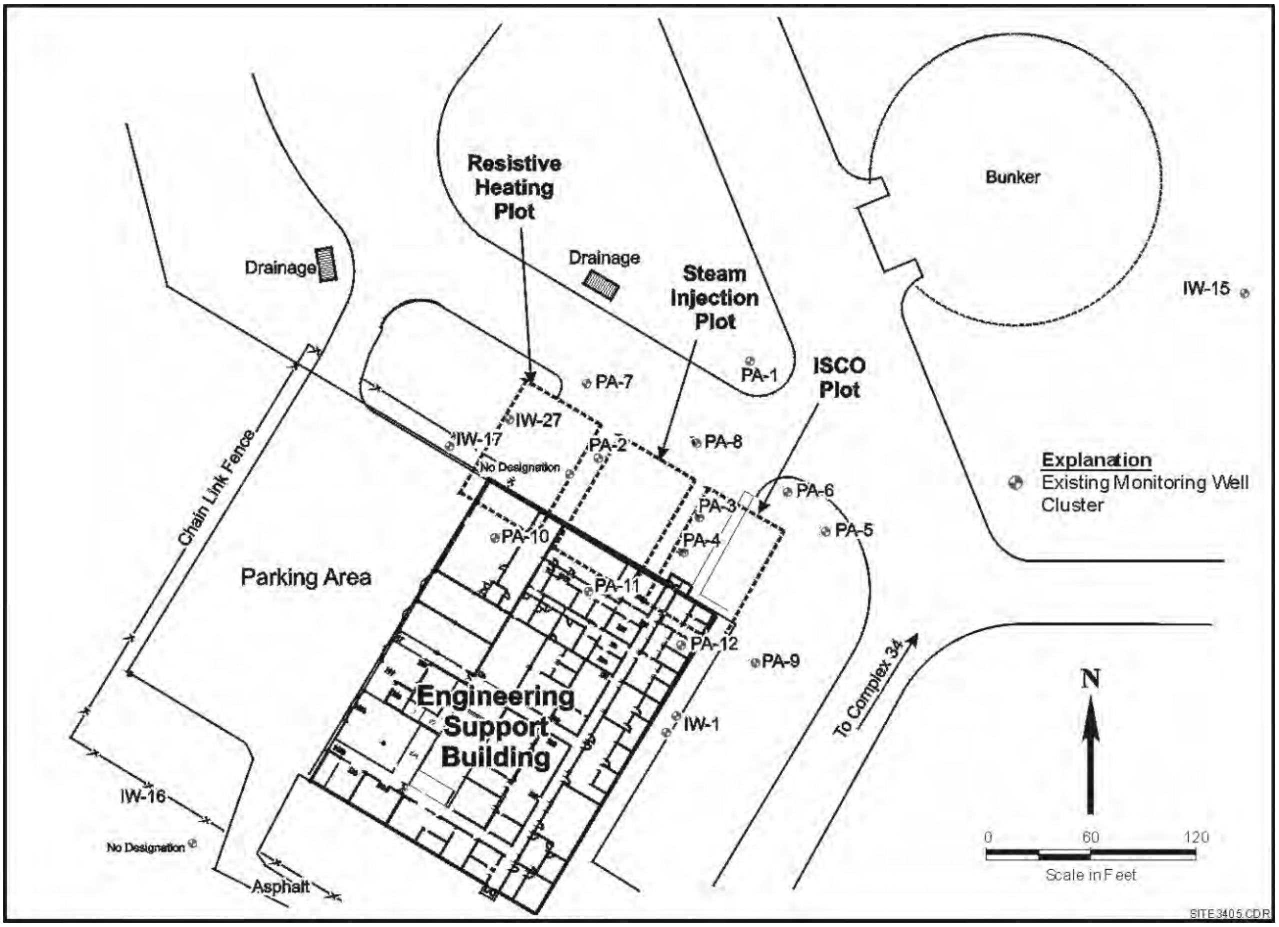

Figure 1-5. Location Map of Launch Complex 34 Site at Cape Canaveral Air Force Station

encompassing different parts of this source zone. Figure 1-5 also shows the layout of the three test plots along the northern edge of the Engineering Support Building at Launch Complex 34. The resistive heating plot is the westernmost (to the right in Figure 1-6) of these plots. Figure 1-6 is a photograph looking southward towards the three test plots and the Engineering Support Building. All three test plots lie partly under the Engineering Support Building so as to encompass the portion of the DNAPL source under the building.

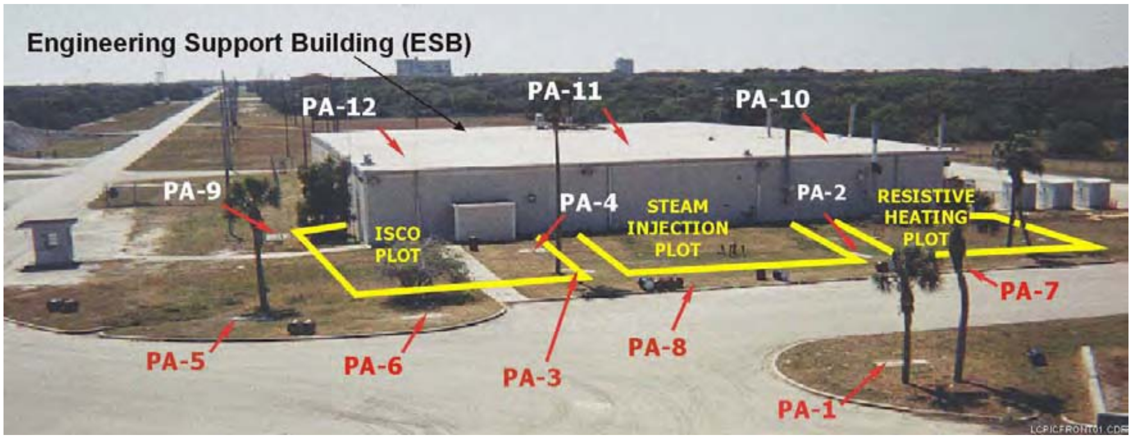

Figure 1-6. Looking Southward towards Launch Complex 34, the Engineering Support Building, and the Three Test Plots

1.5 Technology Evaluation Report Structure

This resistive heating technology evaluation report starts with an introduction to the project organization, the DNAPL problem, the technology demonstrated, and the demonstration site (Section 1). The rest of the report is organized as follows:

- Site Characterization (Section 2)
- Technology Operation (Section 3)
- Performance Assessment Methodology (Section 4)
- Performance Assessment Results and Conclusions (Section 5)
- Quality Assurance (Section 6)
- Economic Analysis of the Technology (Section 7)
- Technology Applications Analysis (Section 8)
- References (Section 9).

Supporting data and other information are presented in the appendices to the report. The appendices are organized as follows:

- Performance Assessment Methods (Appendix A)
- Hydrogeologic Measurements (Appendix B)
- CVOC Measurements (Appendix C)
- Inorganic and Other Aquifer Parameters (Appendix D)
- Microbiological Assessment (Appendix E)
- Surface Emissions Testing (Appendix F)
- Quality Assurance/Quality Control (QA/QC) Information (Appendix G)
- Economic Analysis Information (Appendix H).

2. Site Characterization

This section provides a summary of the hydrogeology and chemistry of the site based on the data compilation report (Battelle, 1999a), the additional site characterization report (Battelle, 1999b), and the pre-demonstration characterization report (Battelle, 1999c).

2.1 Hydrogeology of the Site

A surficial aquifer and a semi-confined aquifer comprise the major aquifers in the Launch Complex 34 area, as described in Table 2-1. The surficial aquifer extends from the water table to approximately 45 ft below ground surface (bgs) in the Launch Complex 34 area. A clay semi-confining unit separates the surficial aquifer from the underlying confined aquifer.

Figures 2-1 and 2-2 are geologic cross sections, one along the northwest-southeast (NW-SE) direction across the middle of the three test plots and the other along the southwest-northeast (SW-NE) direction across the middle of the resistive heating plot. As seen in these figures, the surficial aquifer is subclassified as having an Upper Sand Unit, a Middle Fine-Grained Unit, and a Lower Sand Unit. The Upper Sand Unit extends from ground surface to approximately 20 to 26 ft bgs and consists of unconsolidated, gray fine sand and shell fragments. The Middle Fine-Grained Unit is a layer of gray, fine-grained silty/clayey sand that exists between about 26 and 36 ft bgs. In general, this unit contains soil that is finer-grained than the Upper Sand Unit and Lower Sand Unit, and varies in thickness from about 10 to 15 ft. The Middle Fine-Grained Unit is thicker in the northern portions of the test plots and appears to become thinner in the southern and western portions of the test area (under the Engineering Support Building and in the resistive heating plot). Below the Middle Fine-Grained Unit is the Lower Sand Unit, which consists of gray fine to medium-sized sand and shell fragments. The unit contains isolated fine-grained lenses of silt and/or clay. Figure 2-2 shows a stratigraphic cross section through the demonstration area. The lithologies of thin, very coarse, shell zones were encountered in several units. These zones probably are important as reservoirs for DNAPL.

A 1.5- to 3-ft-thick semi-confining layer exists at approximately 45 ft bgs in the Launch Complex 34 area. The layer consists of greenish-gray sandy clay. The semi-confining unit (i.e., the Lower Clay Unit) was encountered in all borings across the Launch Complex 34 site, and it appears to be a pervasive unit. However, the clay unit is fairly thin in some areas, especially under the resistive heating plot (3 ft thick in most areas, but only 1.5 ft thick under the resistive heating plot). Site characterization data (Battelle, 1999a and b; Eddy-Dilek et al., 1998) suggest that the surfaces of the Middle Fine-Grained Unit and the Lower Clay Unit are somewhat uneven (see Figures 2-3 to 2-5). The Lower Clay Unit slopes downward toward the southern part of all three test plots and toward the center plot and the building (Battelle, 2001b).

Table 2-1. Local Hydrostratigraphy at the Launch Complex 34 Site

Hydrostratigraphic Unit		Thickness (ft)	Sediment Description	Aquifer Unit Description
Surficial Aquifer	Upper Sand Unit	20-26	Gray fine sand and shell fragments	Unconfined, direct recharge from surface
	Middle Fine-Grained Unit	10-15	Gray, fine-grained silty/clayey sand	Low-permeability, semi-confining layer
	Lower Sand Unit	15-20	Gray fine to medium-sized sand and shell fragments	Semiconfined
Lower Clay Unit (Semi-Confining Unit)		1.5-3	Greenish-gray sandy clay	Thin low-permeability semi-confining unit
Semi-Confined Aquifer		>40	Gray fine to medium-sized sand, clay, and shell fragments	Semi-confined, brackish

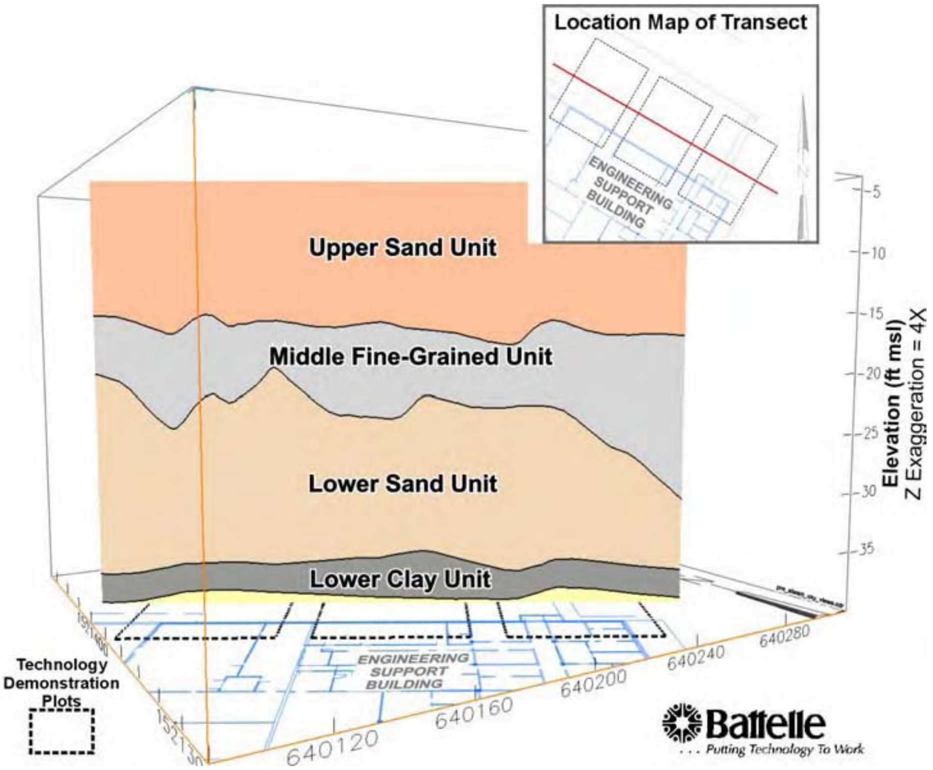

Figure 2-1. NW-SE Geologic Cross Section through the Three Test Plots

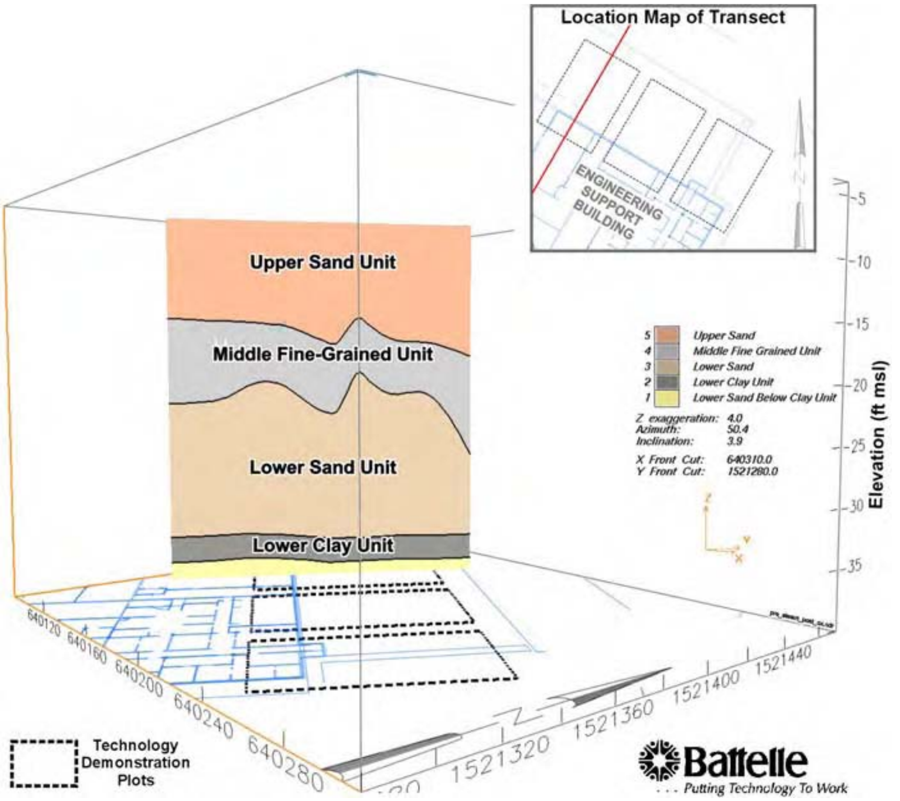

Figure 2-2. SW-NE Geologic Cross Section through Resistive Heating Plot

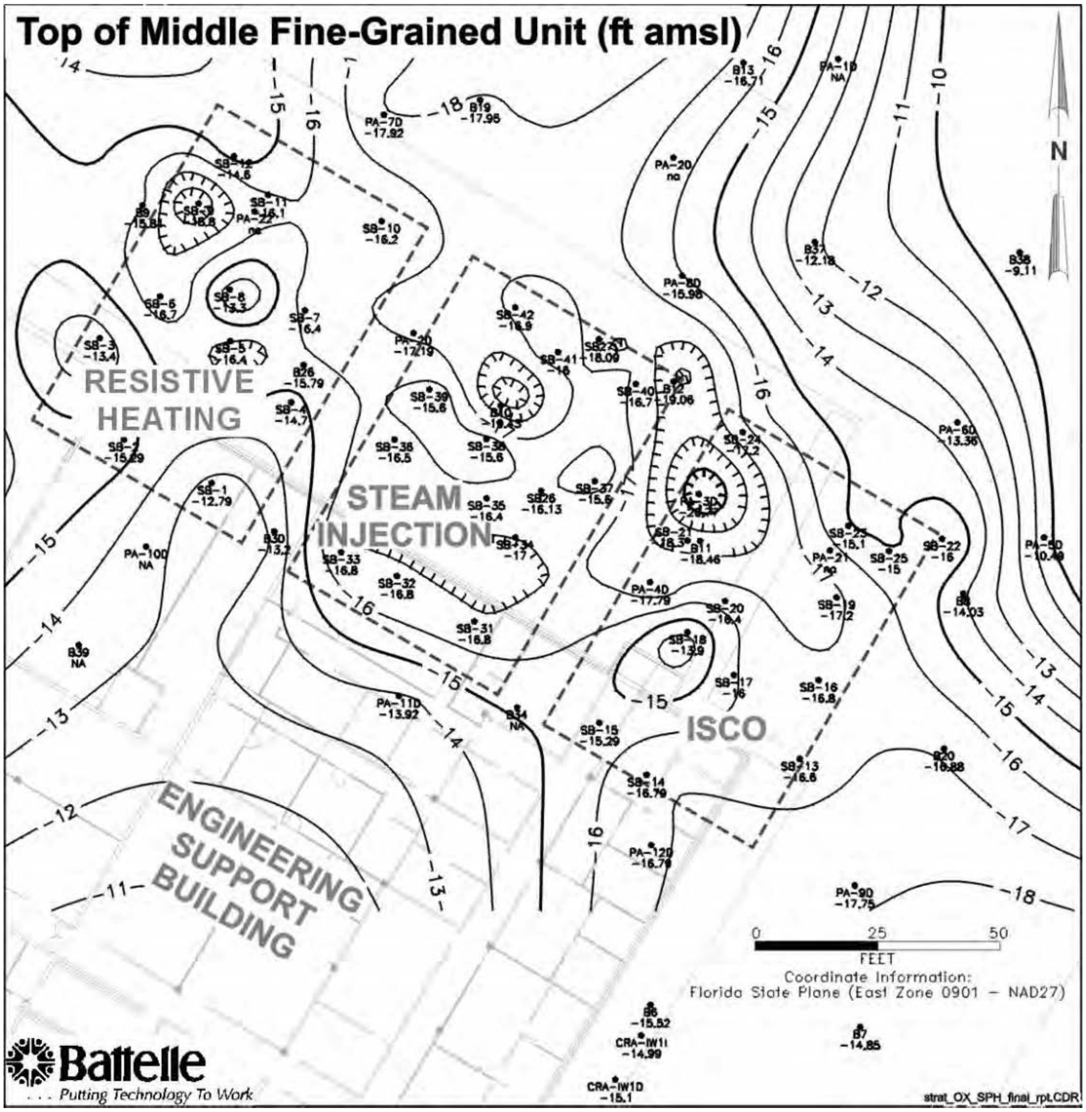

Figure 2-3. Topography of Top of Middle Fine-Grained Unit

The semi-confined aquifer underlies the Lower Clay Unit. During the investigation, the aquifer was found to consist of gray fine to medium-sized sand, clay, and shell fragments to the aquifer below the Lower Clay Unit (Battelle 2001b). Water levels from wells in the aquifer were measured at approximately 4 to 5 ft bgs. Few cores were advanced below the semi-confined aquifer. The thickness of the semi-confined aquifer is between 40 ft and 120 ft.

Water-level surveys were performed in the surficial aquifer in May 1997, December 1997, June 1998, October 1998, and March 1999. Water table elevations in the surficial aquifer were between about 1 and 5 ft mean sea level (msl). In general, the surveys suggest that water levels form a radial pattern with highest elevations near the Engineering Support Building. Figure 2-6 shows a water-table map of June 1998. The gradient and flow directions vary over time at the site. Table 2-2 summarizes the hydraulic gradients and their directions near the Engineering Support Building. The gradient ranged from 0.00009 to 0.0007 ft/ft. The flow direction varied from north-northeast to south-southwest.

Pre-demonstration water-level measurements in all three surficial aquifer zones — Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit — indicate a relatively flat hydraulic gradient in the localized setting of the three test plots, as seen in Figures 2-7 to 2-9 (Battelle, 1999c). On a regional scale, mounding of water levels near the Engineering Support Building generates a radial gradient; the regional gradient across the test plots is weak and appears to be toward the northeast (see Figure 2-6). Probable discharge points for the aquifer include wetland areas, the Atlantic Ocean, and/or the

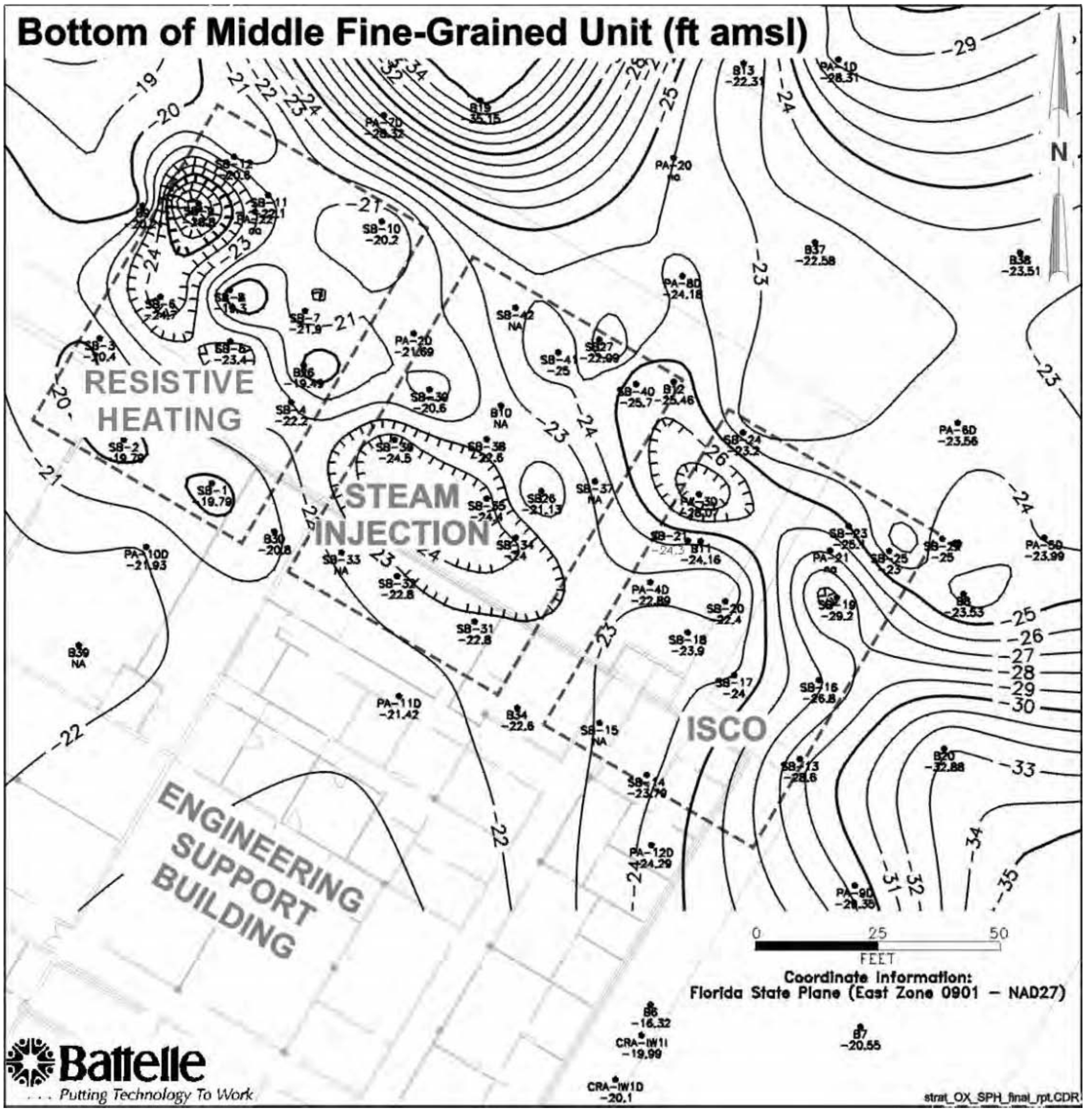

Figure 2-4. Topography of Bottom of Middle Fine-Grained Unit

Banana River. Water levels from wells screened in the Lower Sand Unit usually are slightly higher than the water levels from the Upper Sand Unit and/or the Middle Fine-Grained Unit. The flow system may be influenced by local recharge events, resulting in the variation in the gradients. Recharge to the surficial aquifer is from infiltration of precipitation through surface soils to the aquifer.

In general, pre-demonstration slug tests show that the Upper Sand Unit is more permeable than the underlying units, with hydraulic conductivity ranging from 4.0 to 5.1 ft/day in the shallow wells at the site (Battelle, 1999c). The hydraulic conductivity of the Middle Fine-Grained Unit ranges from 1.4 to 6.4 ft/day in the intermediate wells; measured conductivities probably are higher than the actual conductivity of the unit because the well screens include portions of the Upper Sand Unit. The hydraulic conductivity of the Lower Sand Unit ranged from 1.3 to 2.3 ft/day. Porosity averaged 0.26 in the Upper Sand Unit, 0.34 in the Middle Fine-Grained Unit, 0.29 in the Lower Sand Unit, and 0.44 in the Lower Clay Unit. The bulk density of the aquifer materials averaged 1.59 g/cm^3 (Battelle, 1999b). Ground-water temperatures ranged from 22.4 to 25.7°C during a March 1999 survey.

Water level surveys in the semi-confined aquifer were performed in December 1997, June 1998, and October 1998. Water table elevations were measured at approximately 1 to 5 ft msl, and formed a pattern similar to the pattern formed by surficial aquifer water levels. Groundwater elevations in the semi-confined aquifer are above the semi-confining unit. The gradient in the semi-confined intermediate well screens include portions of the Upper Sand Unit. The hydraulic conductivity of the

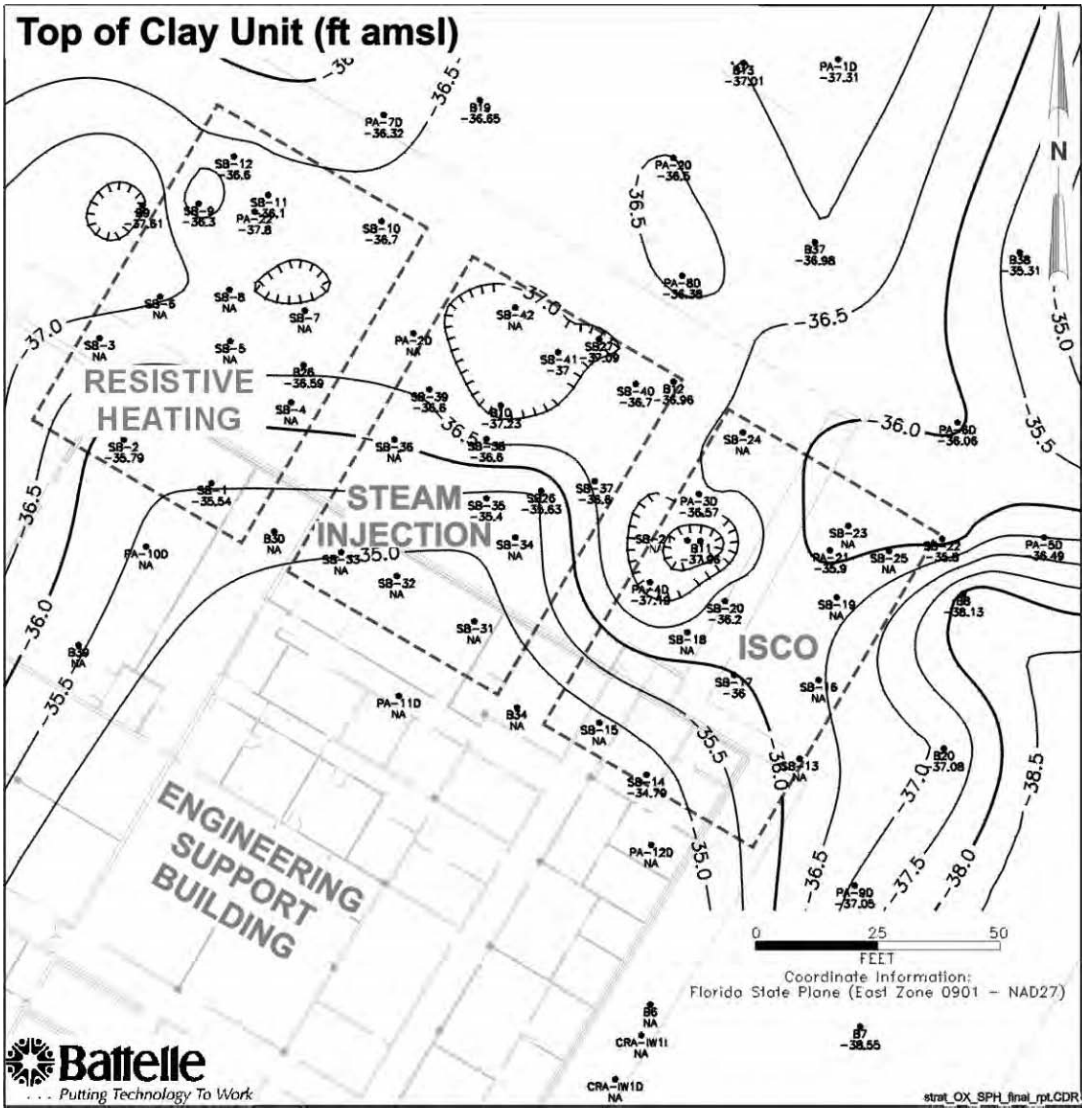

Figure 2-5. Topography of Top of Lower Clay Unit

Lower Sand Unit ranged from 1.3 to 2.3 ft/day. Porosity averaged 0.26 in the Upper Sand Unit, 0.34 in the Middle Fine-Grained Unit, 0.29 in the Lower Sand Unit, and 0.44 in the Lower Clay Unit. The bulk density of the aquifer materials averaged 1.59 g/cm^3 (Battelle, 1999b). Ground-water temperatures ranged from 22.4 to 25.7°C during a March 1999 survey.

Water-level surveys in the semi-confined aquifer were performed in December 1997, June 1998, and October 1998. Water-level elevations were measured at approximately 1 to 5 ft msl, and formed a pattern similar to the pattern formed by surficial aquifer water levels. Groundwater elevations are well above the semi-confining unit, indicating that the aquifer is semi-confined. The gradient in the semi-confined aquifer is positioned in a similar direction to the surficial aquifer. The flow direction varies from east to south-southwest. In general, water levels in the confined aquifer are higher than those in the surficial aquifer, suggesting an upward vertical gradient. Recharge to the aquifer may occur by downward leakage from overlying aquifers or from direct infiltration inland where the aquifer is unconfined. Schmalzer and Hinkle (1990) suggest that saltwater intrusion may occur in intermediate aquifers such as the semi-confined aquifer.

Other notable hydrologic influences at the site include drainage and recharge. Paved areas, vegetation, and topography affect drainage in the area. No streams exist in the site area. Engineered drainage at the site consists of ditches that lead to the Atlantic Ocean or swampy areas. Permeable soils exist from the ground surface to the water table and drainage is excellent. Water infiltrates directly to the water table.

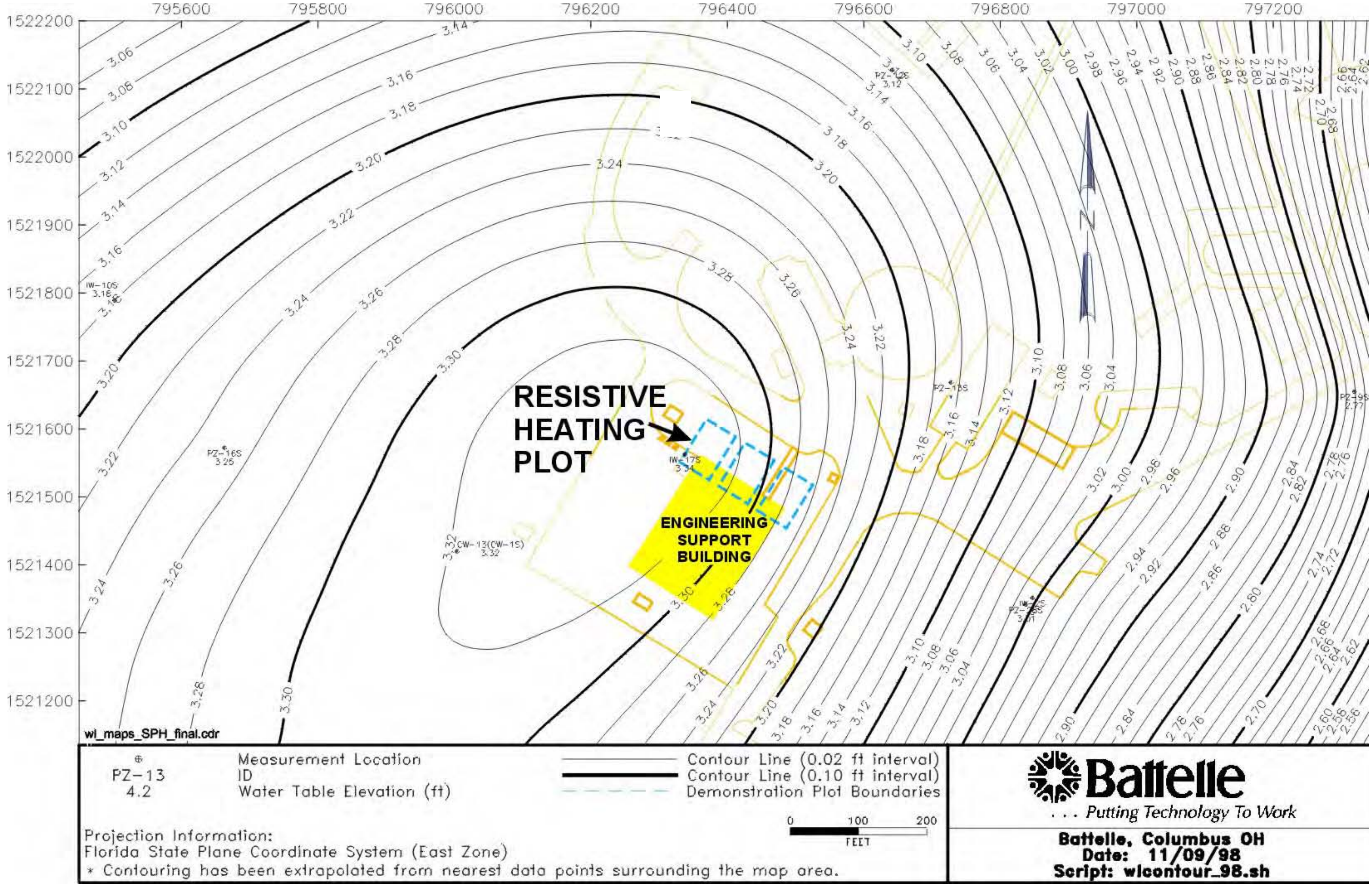

Figure 2-6. Water Table Elevation Map for Surficial Aquifer from June 1998

Table 2-2. Hydraulic Gradients and Directions in the Surficial and Semi-Confined Aquifers

Hydrostratigraphic Unit	Sampling Date	Hydraulic Gradient	Gradient Direction
Surficial Aquifer	May 1997	0.00009	SW
	December 1997	0.0001	SSW
	June 1998	0.0006	WNW
	October 1998	0.0007	NNE
	March 1999	undefined	undefined
Semi-Confined Aquifer	December 1997	0.0008	S
	June 1998	0.0005	E
	October 1998	0.00005	SSW

2.2 Surface Water Bodies at the Site

The major surface water body in the area is the Atlantic Ocean, located to the east of Launch Complex 34. To determine the effects of surface water bodies on the ground-water system, water levels were monitored in 12 piezometers over 50 hours for a tidal influence study during Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) activities (G&E Engineering, Inc., 1996). All the piezometers used in the study were screened in the surficial aquifer. No detectable effects from the tidal cycles were measured, suggesting that the surficial aquifer and the Atlantic Ocean are not well connected hydraulically. However, the Atlantic Ocean and the Banana River seem to act as hydraulic barriers or sinks, as ground water likely flows toward these surface water bodies and discharges into them.

2.3 TCE-DNAPL Contamination in the Resistive Heating Plot and Vicinity

Figures 2-10 to 2-12 show representative pre-demonstration distributions of dissolved TCE, the primary contaminant at Launch Complex 34, in the shallow,

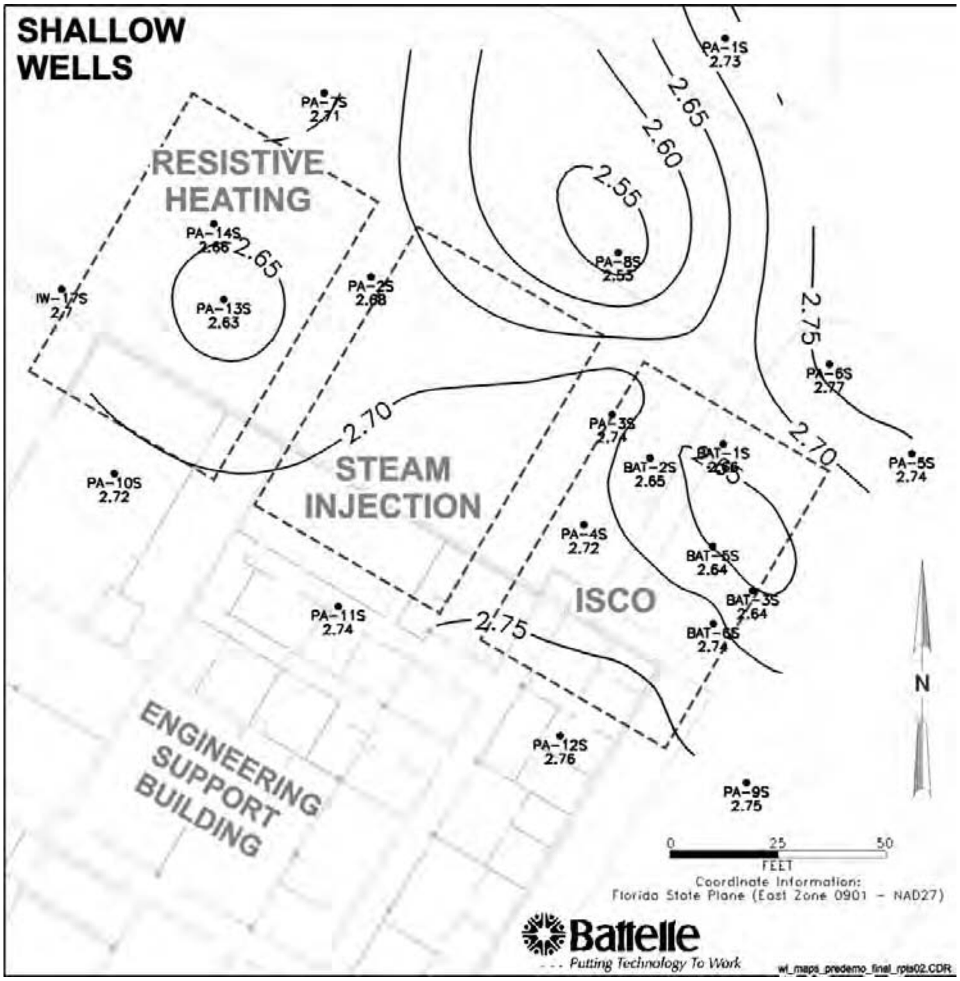

Figure 2-7. Pre-Demonstration Water Levels (as Elevations msl) in Shallow Wells at Launch Complex 34 (September 1999)

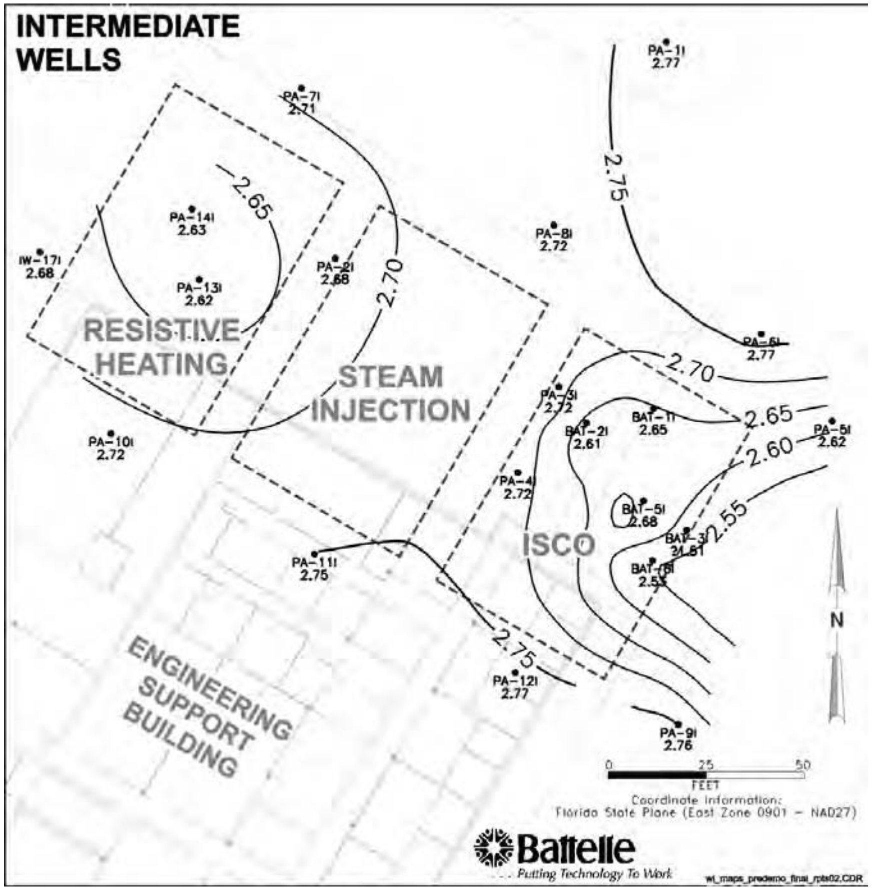

Figure 2-8. Pre-Demonstration Water Levels (as Elevations msl) in Intermediate Wells at Launch Complex 34 (September 1999)

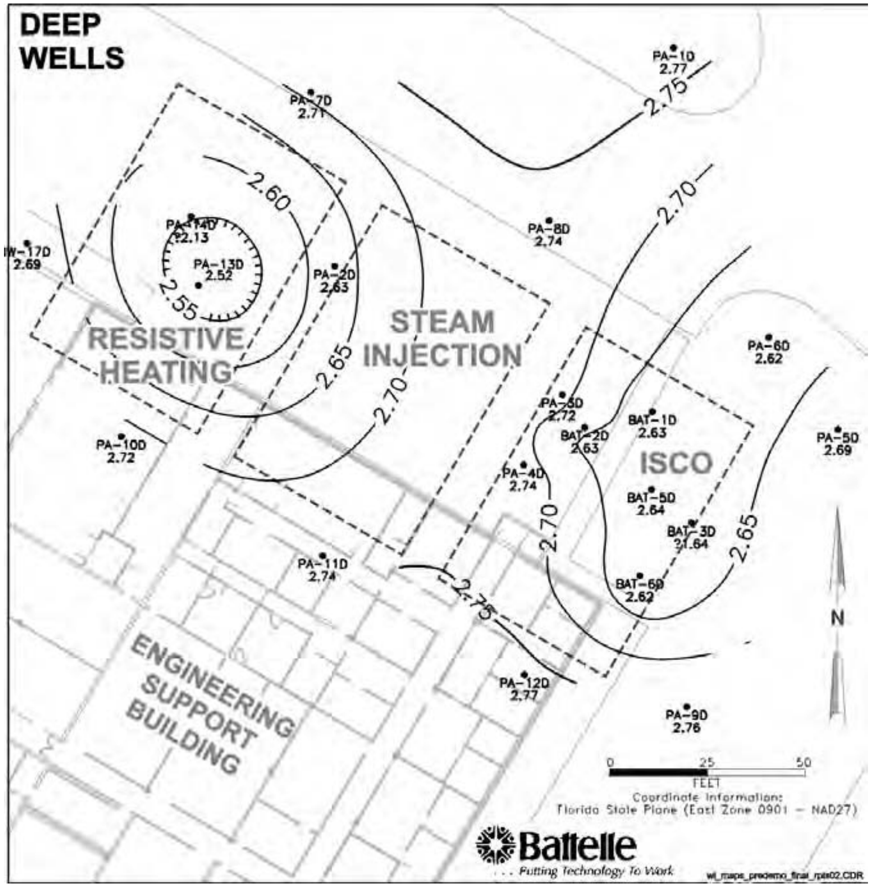

Figure 2-9. Pre-Demonstration Water Levels (as Elevations msl) in Deep Wells at Launch Complex 34 (September 1999)

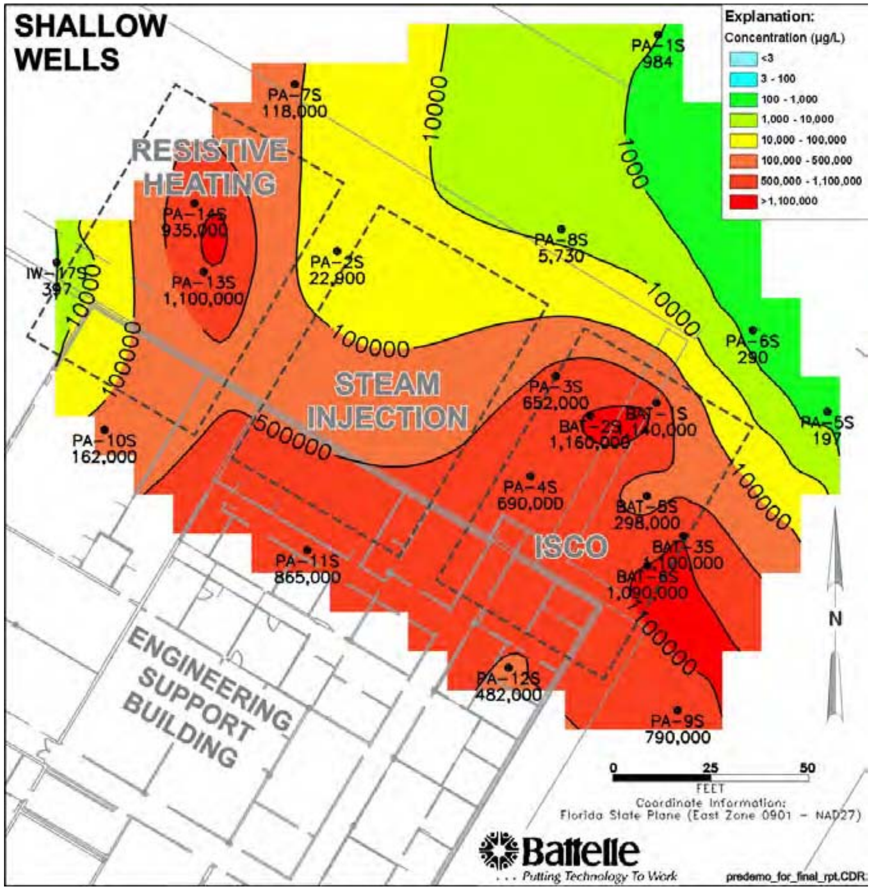

Figure 2-10. Pre-Demonstration Dissolved TCE Concentrations (µg/L) in Shallow Wells at Launch Complex 34 (September 1999)

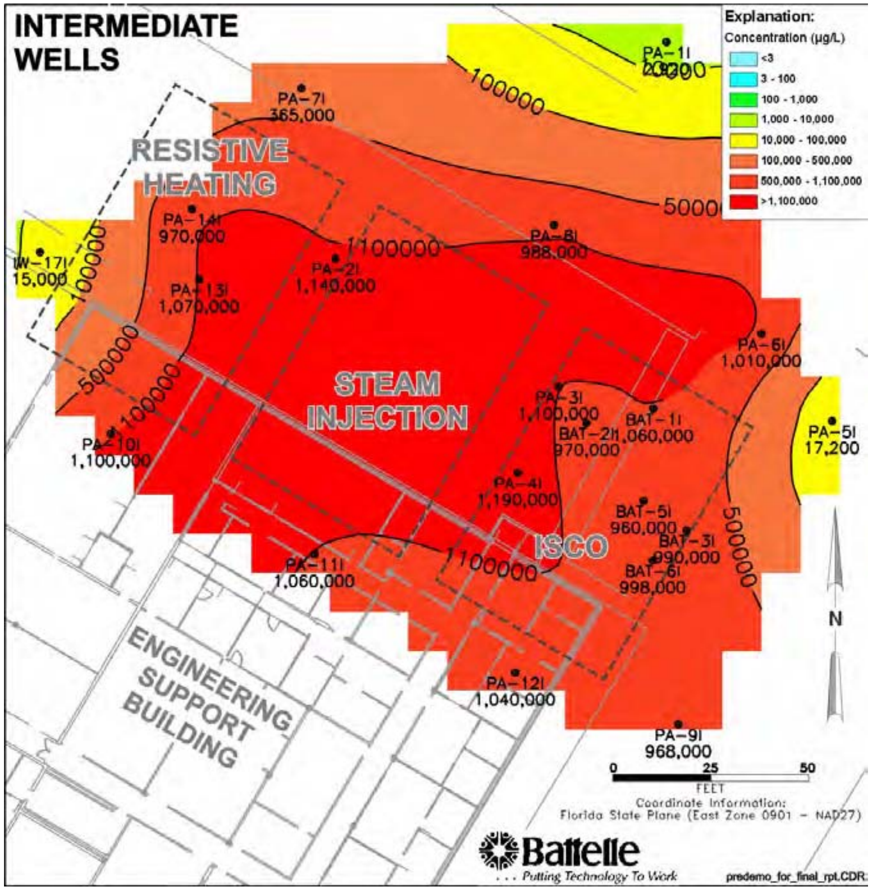

Figure 2-11. Pre-Demonstration Dissolved TCE Concentrations (µg/L) in Intermediate Wells at Launch Complex 34 (September 1999)

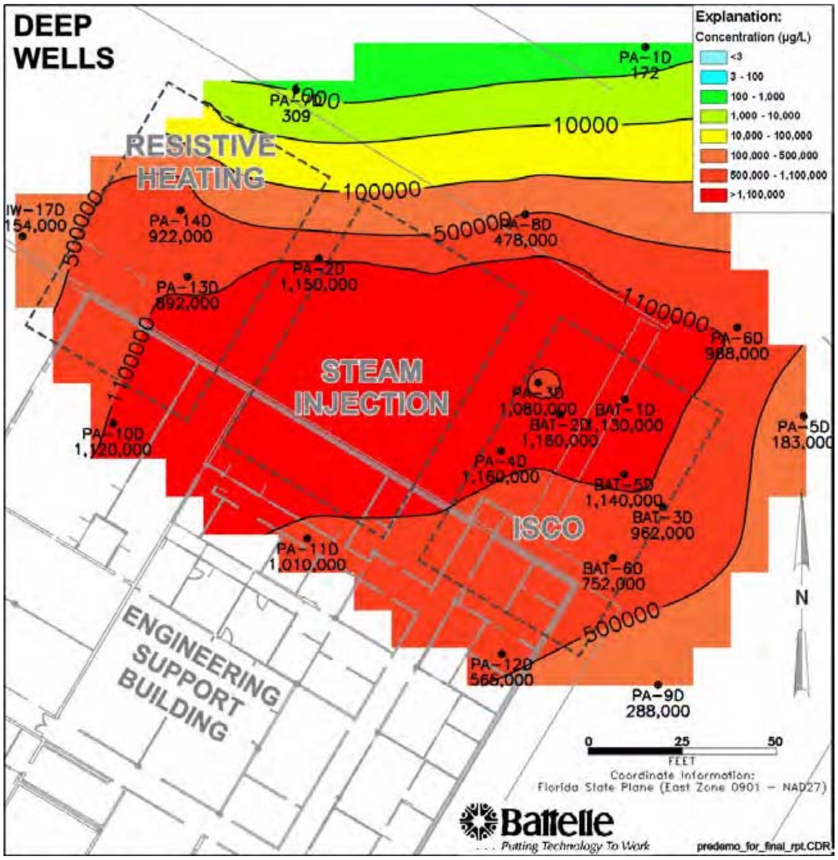

Figure 2-12. Pre-Demonstration Dissolved TCE Concentrations (µg/L) in Deep Wells at Launch Complex 34 (September 1999)

intermediate, and deep wells (Battelle, 1999c). No free-phase solvent was visible in any of the wells during the pre-demonstration sampling; however, ground-water analysis in many wells showed TCE at levels near or above its solubility, indicating the presence of DNAPL at the site. Lower levels of *cis*-1,2-DCE and vinyl chloride are also present in the aquifer, indicating some historical natural attenuation of TCE. Ground-water sampling indicates that the highest levels of TCE are in the Lower Sand Unit (deep wells) and closer to the Engineering Support Building.

Figures 2-13 to 2-15 show representative pre-demonstration horizontal distributions of TCE in soil from the Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit (Battelle, 1999c). TCE levels are highest in the Lower Sand Unit and concentrations indicative of DNAPL extend under the building. As seen in the vertical cross section in Figure 2-16, much of the DNAPL is present in the Middle Fine-Grained Unit and the Lower Sand Unit.

The pre-demonstration soil sampling indicated that approximately 11,313 kg of total TCE was present in the resistive heating plot before the demonstration (Battelle, 1999c). Approximately 10,490 kg of this TCE may occur as DNAPL, based on a threshold TCE concentration of about 300 mg/kg in the soil. This threshold has been determined as the maximum TCE concentration in the dissolved and adsorbed phases in the Launch Complex 34 soil; it was calculated based on properties of the TCE and the subsurface media (the porosity, organic matter content of the soil, etc.) as follows:

$$C_{sat} = \frac{C_{water}\,(K_d \rho_b + n)}{\rho_b} \tag{2-1}$$

where C_{sat} = maximum TCE concentration in the dissolved and adsorbed phases (mg/kg)
C_{water} = TCE solubility (mg/L) = 1,100
ρ_b = bulk density of soil (g/cm^3) = 1.59
n = porosity (unitless) = 0.3
K_d = partitioning coefficient of TCE in soil [(mg/kg)/(mg/L)], equal to ($f_{oc} \cdot K_{oc}$)
f_{oc} = fraction organic carbon (unitless)
K_{oc} = organic carbon partition coefficient [(mg/kg)/(mg/L)].

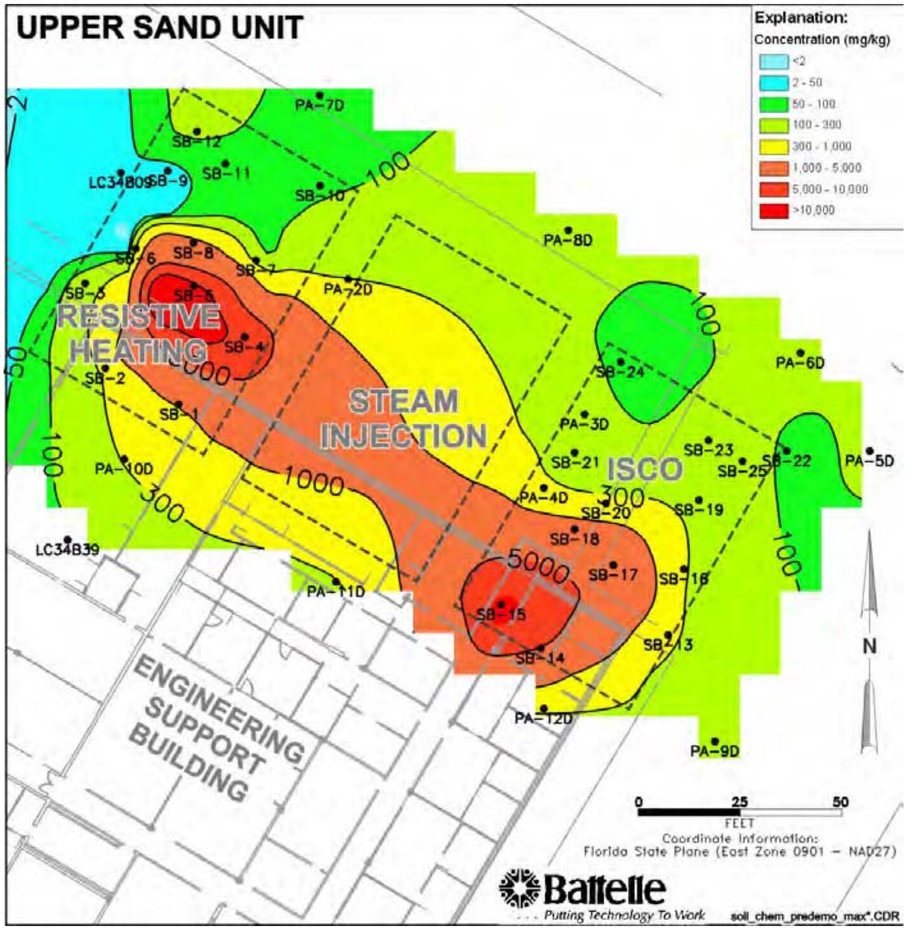

Figure 2-13. Pre-Demonstration TCE Concentrations (mg/kg) in the Upper Sand Unit [–15±2.5 ft msl] Soil at Launch Complex 34 (September 1999)

TCE with concentrations below the threshold value of 300 mg/kg was considered dissolved phase; at or above this threshold, the TCE was considered to be DNAPL. The 300-mg/kg threshold is a conservative estimate and takes into account the minor variability in the aquifer characteristics, such as porosity, bulk density, and organic carbon content. The native organic carbon content of the Launch Complex 34 soil is relatively low and the threshold TCE concentration is driven by the solubility of TCE in the porewater.

In Figures 2-13 to 2-16, the colors yellow to red indicate the least to greatest presence of DNAPL, respectively. As described in Section 4.1.1, contouring software from EarthVision™ was used to divide the plot into isoconcentration shells. A total TCE mass was obtained from multiplying the TCE concentration in each shell by: (1) the volume of the shell; and (2) the bulk density of the soil. To determine the DNAPL mass in the plot, the TCE mass in the shells containing concentrations greater than 300 mg/kg was used. Section 5.1.2 contains a more detailed description of the TCE-DNAPL mass estimation procedures for the resistive heating plot.

2.4 Aquifer Quality/Geochemistry

Appendix A.3 lists the various aquifer parameters measured and the standard methods used to analyze them. Appendix D contains the results of the pre-demonstration ground-water analysis. Pre-demonstration ground-water field parameters were measured in several wells in the demonstration area in August 1999 (Battelle, 1999c). The pH was relatively constant with depth, and ranged from 6.9 to 7.5. Dissolved oxygen (DO) levels were measured with a flowthrough cell, and were mostly less than 1 mg/L in the deep wells, indicating that the aquifer was anaerobic, especially at greater depths. Oxidation-reduction potential (ORP) from all the sampled wells ranged from –142 to –74 millivolts (mV). Total organic carbon (TOC) concentrations ranged from 6 to 40 mg/L in water samples and from 0.9 to 1.7% in soil samples; much of this TOC is probably TCE-DNAPL, as the samples were collected from the DNAPL source region. Biological oxygen demand (BOD) ranged from <3 to 20 mg/L in ground water.

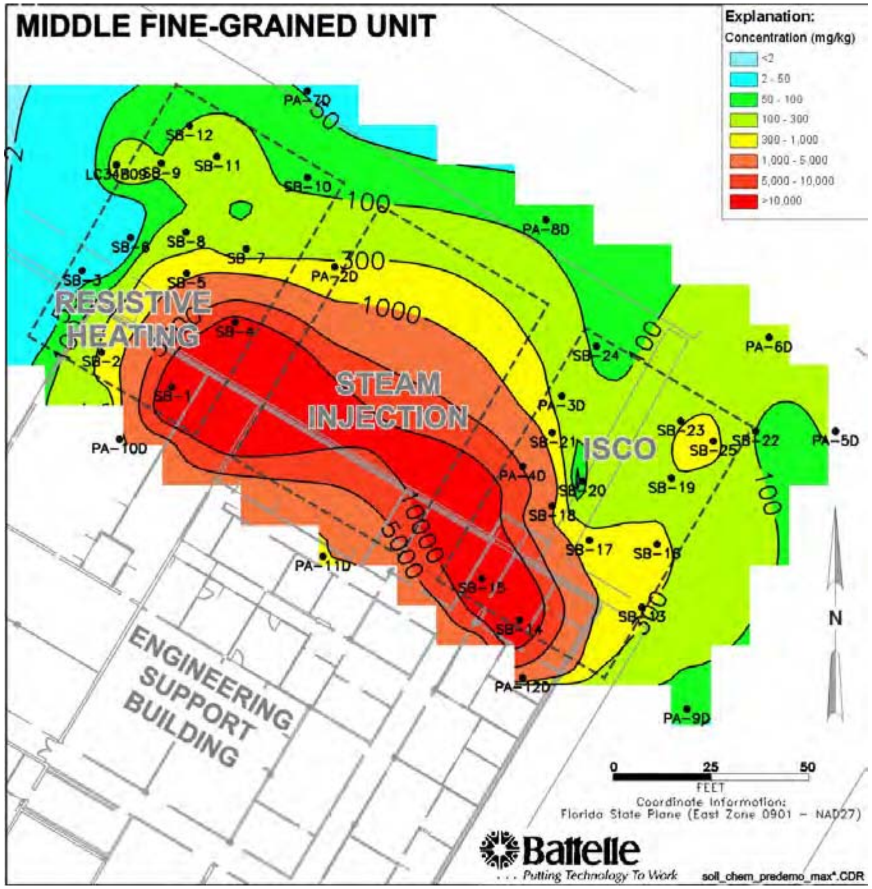

Figure 2-14. Pre-Demonstration TCE Concentrations (mg/kg) in the Middle Fine-Grained Unit [-20±2.5 ft msl] Soil at Launch Complex 34 (September 1999)

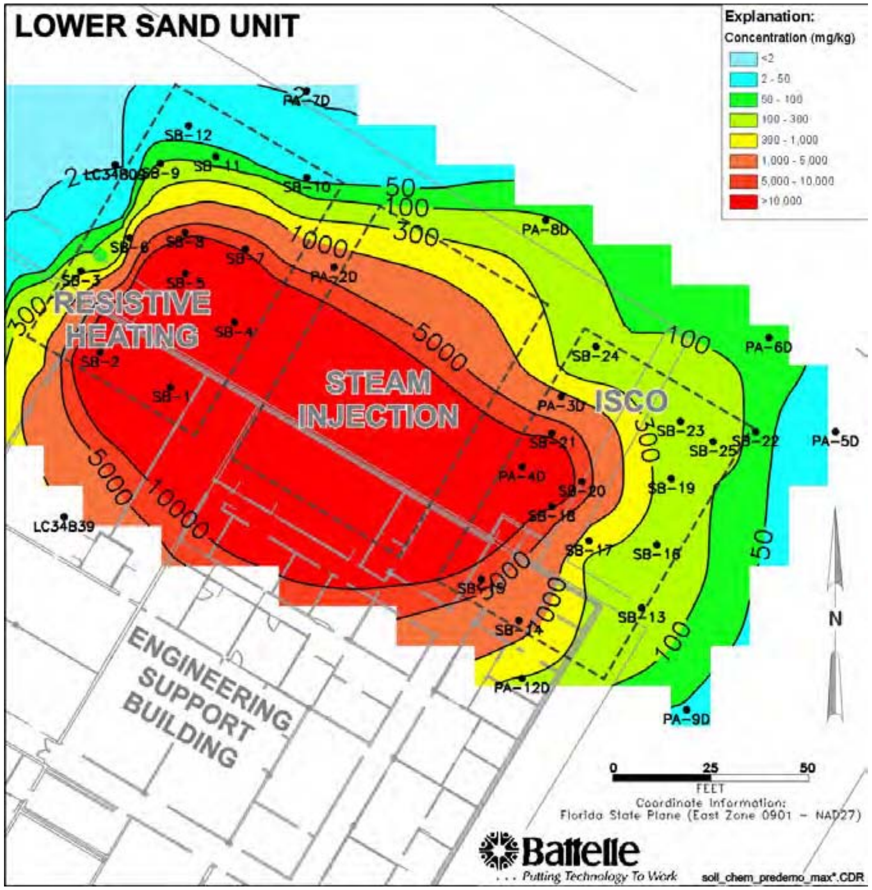

Figure 2-15. Pre-Demonstration TCE Concentrations (mg/kg) in the Lower Sand Unit [–35 ±2.5 ft msl] Soil at Launch Complex 34 (September 1999)

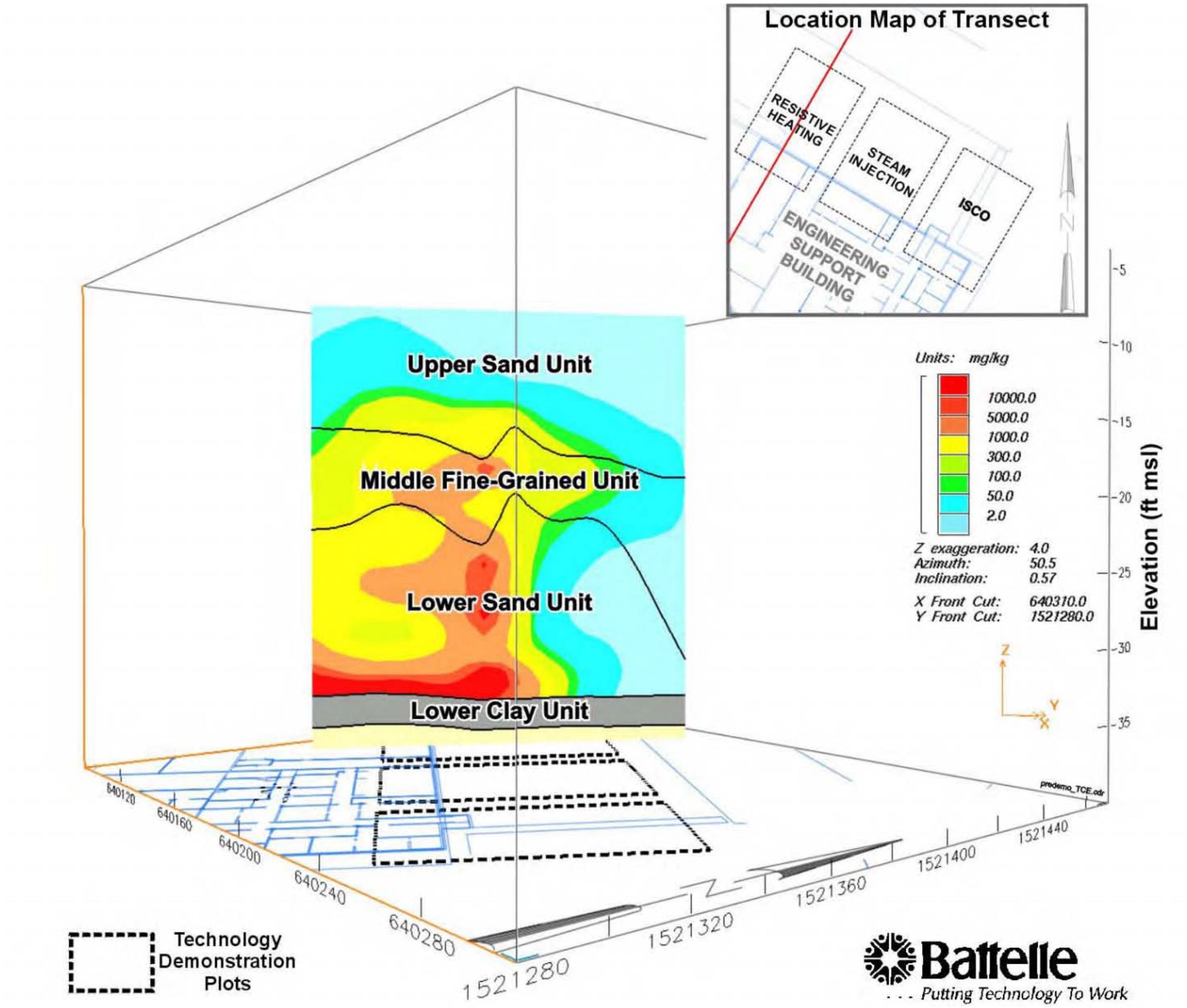

Figure 2-16. Vertical Cross Section through Resistive Heating Plot Showing TCE Concentrations (mg/kg) in the Subsurface

Inorganic ground-water parameters were tested in August 1999 in select wells to determine the pre-demonstration quality of the ground water in the target area (Battelle, 1999c). Inorganic parameters in the ground water at Launch Complex 34 are summarized as follows:

- Total dissolved solids (TDS) concentrations increased sharply with depth, suggesting that the water becomes more brackish with depth. The TDS levels ranged from 548 to 1,980 mg/L. Chloride concentrations ranged from 11 to 774 mg/L and increased sharply with depth, indicating some saltwater intrusion in the deeper layers. These high levels of native chloride made a chloride mass balance (a possible indicator of TCE degradation) difficult during the performance assessment. Sodium, another major seawater constituent, ranged from 17 to 369 mg/L and also increased sharply with depth.
- Alkalinity levels ranged from 337 to 479 mg/L and showed little trend with depth or distance.
- Iron concentrations ranged from <0.05 to 11 mg/L in the ground water, and manganese concentrations ranged from <0.015 to 1.1 mg/L with little vertical or lateral trend.

- Calcium concentrations ranged from 60 to 143 mg/L and magnesium concentrations ranged from 23 to 113 mg/L. Both parameters appeared to increase slightly with depth.
- Sulfate concentrations were between 39 and 104 mg/L and showed no discernable trends. Nitrate concentrations were below detection.

2.5 Aquifer Microbiology

A separate exploratory microbiological study was conducted in the pre-demonstration and post-demonstration aquifer in the resistive heating plot under a Work Plan prepared by Battelle and Lawrence Berkeley National Laboratory (Battelle, 2000d). The approach and preliminary results of this study are presented in Appendix E.

3. Technology Operation

This section describes how the resistive heating technology was implemented at Launch Complex 34.

3.1 Resistive Heating Concept

As described in Figure 1-3 and Section 1.3, the resistive heating technology uses a strong voltage (of the order of 500 kW or more) to generate resistive heating of subsurface soils. Volatile and semivolatile contaminants are removed from the subsurface by a combination of direct volatilization and steam stripping. A surface plenum and/or vadose zone piping are used to extract the vaporized contaminants and steam to the ground surface, where they are condensed and treated. Part of the vadose zone is heated by the rising steam and this prevents recondensation of the contaminant vapors.

The aboveground system typically consists of a water-cooled condenser and activated carbon. The off-gas from the carbon is discharged to the atmosphere. The condensate may be treated on site or disposed off site. The condensate and spent carbon typically are the wastestreams generated by resistive heating treatment. Recent reports have also claimed that organic contaminants degrade in situ due to heat-accelerated abiotic and/or biotic processes. Abiotic processes may include hydrolysis and/or oxidation.

3.2 Application of Resistive Heating at Launch Complex 34

In the IDC demonstration, resistive heating was used for heating a DNAPL source zone consisting primarily of TCE. Lesser amounts of dissolved *cis*-1,2-DCE were also present in the aquifer at Launch Complex 34, the site of the demonstration. For the purpose of the demonstration, the relatively large source zone was divided into three test plots for three different technology applications. The 75-ft × 50-ft test plot assigned to the resistive heating technology is shown in Figure 3-1 and is referred to as the resistive heating plot. The ISCO and resistive heating technology demonstrations were conducted concurrently in the two outer plots, which are separated by about 80 ft. The steam injection demonstration was conducted after completing the resistive heating and ISCO demonstrations.

In their draft-final report (CES, 2001) on the IDC demonstration, the vendor has provided a detailed description of their resistive heating equipment, application methodology, and process measurements. A summary description of the resistive heating process implemented by the vendor at Launch Complex 34 follows in this section. Table 3-1 includes a chronology of events constituting the resistive heating demonstration. The field application of the technology was conducted over a period of 11 months from August 1999 to July 2000. The vendor experienced some periods of downtime. An unexpected interruption occurred from September 30 to December 12 after two hurricanes damaged the power supply. Also, changing the power supply caused an additional interruption in early 2000.

3.2.1 Resistive Heating Equipment and Setup at Launch Complex 34

Figure 3-2 is a photo of the resistive heating system installed at Launch Complex 34. As shown in the equipment layout in Figure 3-3, the resistive heating system at Launch Complex 34 used 13 electrodes. Three of the electrodes that were near the Engineering Support Building were installed at an angle of 18 degrees to provide heat to the 15 ft of test plot that lies under the building. To protect the thin aquitard, the electrodes were completed slightly above the Lower Clay Unit. Each electrode consisted of two conductive intervals—one from 23 to 30 ft bgs (in the Upper Sand Unit) and the other from 38 to 45 ft bgs (in the Lower Sand Unit). The lower heating interval was configured to provide a “hot floor” for the treated aquifer and to mitigate the potential for downward migration of DNAPL. The upper conductive interval was configured to provide heat to the Upper Sand Unit and the Middle Fine-Grained Unit.

Twelve soil vapor extraction (SVE) wells were installed with 2-ft screens to depths of 4 to 6 ft bgs to recover the

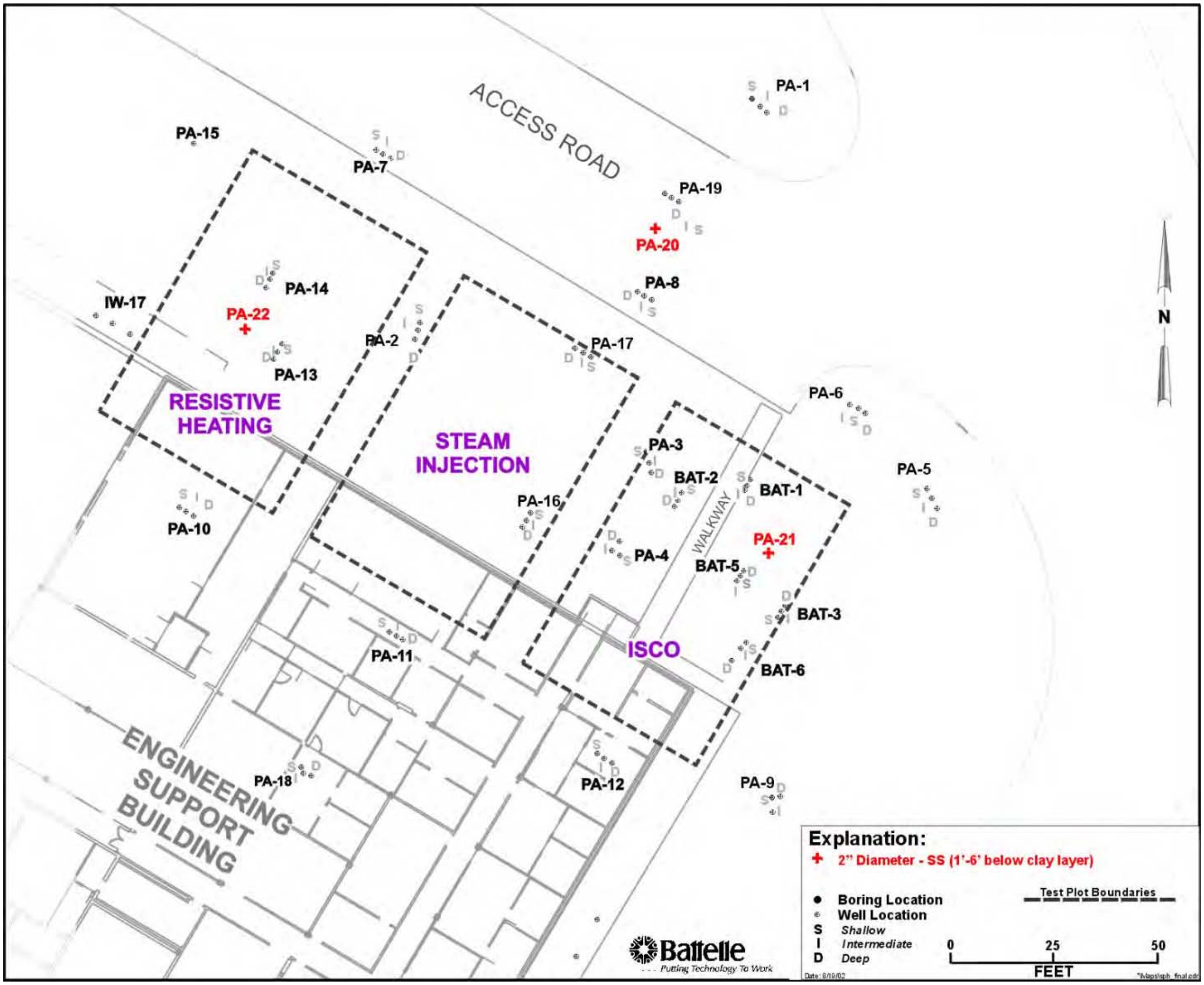

Figure 3-1. Resistive Heating Plot and Monitoring Well Layout for Performance Assessment

vapors. The extracted vapor and steam were passed through an air-water knockout drum, a heat exchanger, a condensate collection drum, and a centrifugal blower. The off-gas from the blower was treated by a 20,000-lb vessel of granular activated carbon (GAC). Additional treatment of the off-gas to remove vinyl chloride was accomplished by a 1,000-lb vapor-phase GAC vessel, followed by an 800-lb silica polish bed impregnated with potassium permanganate. The steam condensate was pumped through a 1,000-lb liquid-phase GAC vessel to a cooling tower, where it was evaporated to provide cooling for the heat exchange process. Excess condensate was transferred to a 6,500-gal storage tank.

At the end of the demonstration, the stored condensate was analyzed and transported to the on-site wastewater treatment facility. The GAC was analyzed and shipped to an off-site facility for regeneration. The permanganate-impregnated silica was disposed of in a landfill.

3.2.2 Resistive Heating Field Operation

The vendor prepared and submitted a draft-final report (CES, 2001) describing the details of the resistive heating system setup and operation at Launch Complex 34. This section summarizes the resistive heating operation described in this report and observed during the demonstration. As shown in Table 3-1, the resistive heating heat application began on August 18, 1999 and continued until July 12, 2000, with two major breaks in between. The SVE system was operated for two more

Table 3-1. Timeline for Resistive Heating Technology Demonstration

Start Date	End Date	Number of Days	Events/Heat Application Stage	Energy Applied during this Time Period (kW-hrs)	Temperature (°C) at Top/Bottom of Aquifer at the start of time period	Temperature (°C) at Top/Bottom of Aquifer at the end of time period	Comments
	6/18/98		Solicitation received from IDC	—	—	—	
			Design/modeling/ treatability tests	—	—	—	
	7/1/99		IDC approval to proceed	—	—	—	
7/29/99 6/3/99	8/17/99		Mobilization to site and setup	—	—	—	
4/1/00	6/25/00	90	Test Plan/Quality Assurance Project Plan (QAPP)	—	—	—	
6/21/00	7/17/00	27	Pre-demonstration characterization of resistive heating plot	—	—	—	
8/18/00	9/30/00	43	First heat application	216,915	30/24	47/92	
9/30/99	12/12/99	77	Break	—	—	—	Hurricane damaged step-down transformer in power supply/TCE concentration in ditch adjacent to treatment cell
12/12/99	3/24/00	98	Second heat application	821,100	39/75	100/124	2/28-3/2. Upgrade electrodes to enhance power input.
3/24/00	5/11/00	48	Break	—	—	—	Heating near septic tank/ power supply replacement/ delay resulting from rocket launches
5/11/00	7/12/00	62	Third heat application	687,800	60/82	100/124	
7/12/00	9/19/00	79	Heating off, vapor recovery system on	—	—	—	To evacuate any TCE vapors generated while the aquifer is at elevated temperature
8/1/00	12/31/00	120	Post-demonstration characterization	—	—	—	

Figure 3-2. Resistive Heating System in Operation at Launch Complex 34

months until September 19, 2000 so that continuing vapors from the still hot aquifer could be recovered. Over the course of the demonstration, a total of 1,725,000 kW-hrs of energy was applied to the subsurface. The applied voltage ranged from 100 to 500 V, which resulted in an electrical current of 10 to 400 amps.

At this site, the vendor used a novel electrode design consisting of an electrical cable attached to a ground rod within a graphite backfill, instead of the traditional pipe electrode. However, this new design, coupled with excessive rainfall and a rising water table, resulted in insufficient heating in the shallow portion of the Upper Sand Unit. Therefore, between February 24 and March 2, 2000, the vendor installed ground rods near each electrode to heat the 3- to 10-ft-bgs ground interval.

The first major interruption of the resistive heating operation occurred between September 30 and December 12, 1999. On September 10 a major hurricane (Hurricane Floyd) hit Cape Canaveral, followed by a second hurricane (Hurricane Irene) on October 17, 1999. The power supply was damaged and the water table rose significantly, from about 6 ft bgs before the demonstration to almost 1.5 ft bgs in monitoring well PA-2. In low-lying areas of the test plot, the ground water was probably near the ground surface. Elevated TCE levels discovered in ponded surface water in a ditch along the west side of the resistive heating plot indicate that some TCE migrated from the plot during this period. It is probable that infiltration of cooler rainwater from the storms caused the rising TCE vapors to condense near the ground surface. Typically, the buoyancy of the hot water generated in the plot leads to a convection cycle, in which hot water builds up near the water table and migrates sideways out of the plot. This loss of water is made up by cooler water entering from the bottom of the test plot, near the aquitard. During the hurricanes and the consequent high rainfall events, the hot ground water laden with TCE near the water table possibly migrated westward from the plot along the surface topographic gradient. In addition, the rising water table submerged the SVE wells, rendering them useless; it is possible that some TCE volatilized to the atmosphere during this time.

In October 1999, the vendor modified the design during the demonstration and installed six horizontal wells in the northern half of the cell and seven shallow vertical wells in the southern half of the cell near the building. In addition, a surface cover (plenum) was placed over the plot to improve vapor capture. In November 1999 the plenum was expanded and two additional horizontal wells were installed. The plenum was expanded again in March 2000 on the west side of the plot, after surface emission tests and dried vegetation indicated that hot vapors were probably reaching the ground surface there. In October 1999, the vendor also installed a drainage diversion system consisting of a sandbag cutoff wall on the east side of the plot and a sump pump to divert the water through a PVC pipe to the drainage collection area in the west. Also, PVC risers on the six monitoring wells inside the plot were beginning to melt down because of the heat conducted by the stainless steel wells below. These risers were removed and replaced with stainless steel risers. During the repair, surrounding aquifer materials got into well casings of performance monitoring wells (PA-13 and PA-14). The monitoring wells had to be cleaned out later by surge-and-purge to pump out the sediments inside the well casings. Due to these modifications and the repairs resulting from the hurricanes, the resistive heating system was operated only for six weeks during the first heating cycle. The second heating cycle started on December 12, 1999, and continued for 13 weeks.

On March 24, 2000, operations were interrupted to replace the transformer, a major piece of equipment, on which the lease had run out. A replacement transformer was obtained and installed in April, but the third heating cycle could begin only on May 11, 2000 due to an unusually heavy space shuttle launch schedule that necessitated work stoppages. The third heating cycle continued for eight weeks until July 12, 2000, when the IDC determined that VOC extraction rates had declined significantly. The SVE system remained operational until September 19, 2000, by which time subsurface temperatures had fallen below 95°C, indicating that steaming had stopped.

During the demonstration, the vendor monitored VOC levels and flowrate of the extracted vapor stream. The

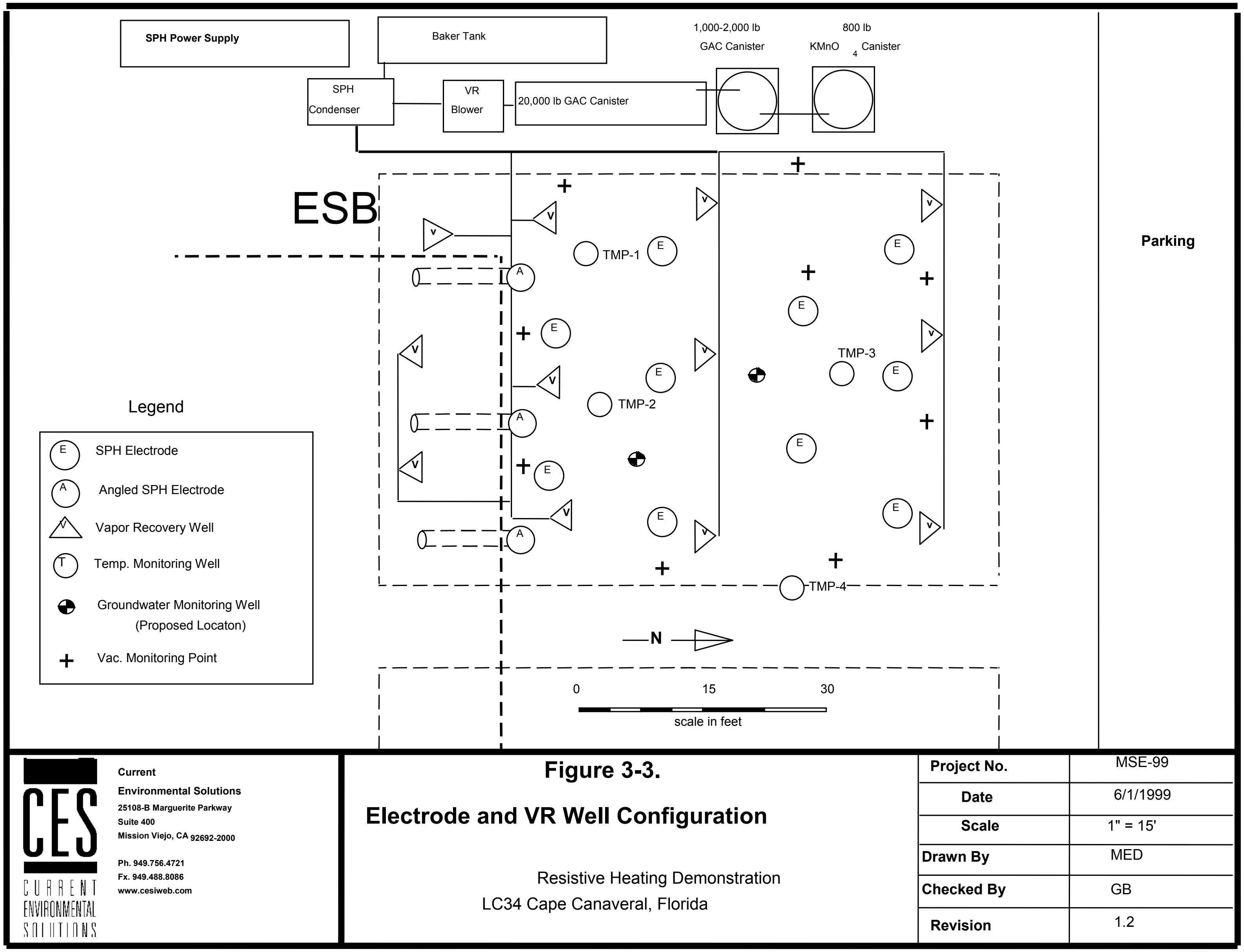

Figure 3-3. Resistive Heating System Layout at Launch Complex 34

vendor also monitored temperatures in the plot through the four thermocouple bundles (TMP-1 through TMP-4, shown in Figure 3-3). This monitoring was separate from the performance assessment conducted by Battelle and was done primarily to make operational decisions.

3.2.3 Health and Safety Issues

A major initial concern with the resistive heating technology was the high voltage (up to 500 V) required to be delivered to the subsurface. Despite all the difficulties involving hurricanes and flooding of the plot, the vendor successfully controlled the transport and distribution of the large amounts of electricity involved. At all times, the ground surface was insulated from the electric current running through the aquifer. The ground surface above the resistive heating plot was available for other activities during the voltage applications. This successful management of the high voltage application is probably the most important safety achievement of the demonstration.

The voltage application was turned off whenever monitoring wells were sampled inside the test plot and all sampling events were conducted safely. Because the monitoring well screens were completely submerged under the water table, there was steam pressure buildup in the monitoring wells. It was agreed that the initial procedure was to open the well caps slowly to release any pressure. Sampling personnel wore heat-resistant gloves and face shields when opening the wells.

However, on one occasion, a jet of steam rose from the wellhead and continued for several seconds. Subsequently, a pressure gauge and pressure release valve were installed on each monitoring well inside the plot and along the perimeter. This seemed to help; but there were times when, despite releasing the pressure in the wells until the pressure gauge showed zero, steam still came rushing out in a jet above the well during sampling. There were no injuries, as sampling personnel were alert to the sounds of steam welling up in the well; however, monitoring the inside of the hot treated plot continued to be a necessary, but difficult task.

System operators and sampling personnel wore Level D personal protective equipment at the site. Heavy equipment movement during mobilization and demobilization and handling of hot fluids were hazards that were recognized in the Health and Safety Plan prepared at the beginning of the demonstration. No injuries were encountered during the demonstration.

4. Performance Assessment Methodology

Battelle, in conjunction with the U.S. EPA SITE Program and TetraTech EM, Inc., conducted an independent performance assessment of the resistive heating demonstration at Launch Complex 34 (see Figure 4-1). The objectives and methodology for the performance assessment were outlined in a QAPP prepared before the field demonstration and reviewed by all stakeholders (Battelle, 1999d). The objectives of the performance assessment were:

- Estimating the change in TCE-DNAPL mass
- Evaluating changes in aquifer quality due to the treatment
- Evaluating the fate of TCE-DNAPL removed from the resistive heating plot
- Verifying resistive heating operating requirements and costs.

The first objective, estimating the TCE-DNAPL mass removal percentage, was the primary objective. The rest were secondary objectives in terms of demonstration focus and resources expended. Table 4-1 summarizes the four objectives of the performance assessment and the methodology used to achieve them.

Figure 4-1. Sampling for Performance Assessment at Launch Complex 34

4.1 Estimating the Change in TCE-DNAPL Mass in the Plot

The primary objective of the performance assessment was to estimate the change in mass of total TCE and DNAPL. Total TCE includes both dissolved- and free-phase TCE present in the aquifer soil matrix. DNAPL refers to free-phase TCE only and is defined by the threshold TCE concentration of 300 mg/kg described in Section 2.3. Soil sampling in the resistive heating plot before and after the demonstration was the method used for estimating TCE-DNAPL mass changes.

At the outset of the demonstration, the Technical Advisory Group proposed 90% DNAPL mass removal as a target for the three remediation technologies being demonstrated. This target represented an aggressive treatment goal for the technology vendors. Soil sampling was the method selected in the QAPP for determining percent change in TCE-DNAPL mass at this site. Previous soil coring, sampling, and analysis at Launch Complex 34 (Battelle, 1999b; Eddy-Dilek et al., 1998) had shown that this was a viable technique for identifying the boundaries of the DNAPL source zone and estimating the DNAPL mass. The advantage of soil sampling was that relatively intensive horizontal and vertical coverage of the resistive heating plot, as well as of the dissolved-phase TCE and DNAPL distribution, could be achieved with a reasonable number of soil samples and without DNAPL access being limited to preferential flowpaths in the aquifer.

The primary focus of the performance assessment was on TCE, *cis*-1,2-DCE and vinyl chloride in the soil samples. However, high TCE levels often masked the other two compounds and made their detection difficult.

The statistical basis for determining the number of soil coring locations and number of soil samples required to be collected in the resistive heating plot is described in Appendix A.1. Based on the horizontal and vertical

Table 4-1. Summary of Performance Assessment Objectives and Associated Measurements

Objective	Measurements	Sampling Locations[(a)]
Estimating TCE-DNAPL mass removal	CVOCs in soil; before and after treatment	12 spatial locations, every 2-ft depth interval
Evaluating changes in aquifer quality	CVOCs in ground water; before, during, and after treatment	Primary well clusters PA-13 and PA-14
	Field parameters in ground water; before, during, and after treatment	Primary well clusters PA-13 and PA-14; perimeter wells[(b)] for verifying spread
	Inorganic parameters in ground water (cations, anions, including alkalinity); before and after treatment	Primary well clusters PA-13 and PA-14; perimeter wells[(b)] for verifying spread
	TOC in soil; before and after treatment	Two locations, three depths inside plot
	TDS and BOD; before and after treatment	Primary well clusters PA-13 and PA-14
	Hydraulic conductivity; before and after treatment	Primary well clusters PA-13 and PA-14
Evaluating fate of TCE-DNAPL	Chloride in ground water	Primarily well clusters PA-13 and PA-14 in the plot; perimeter wells[(b)]
	Inorganics in ground water	Primary well clusters PA-13 and PA-14
	Hydraulic gradients	All wells
	CVOCs in soil surrounding the plot; before and after treatment	Fourteen locations outside the resistive heating plot (See Figure 4-3)
	CVOCs and inorganics in soil and ground water in the confined aquifer	Wells PA-20, PA-21, and PA-22
	Surface emissions; primarily during oxidant injection	Three locations inside plot or around the plenum; 3 background locations
Verify operating requirements and cost	Field observations; tracking materials consumption and costs	Field observations by vendor and Battelle; materials consumption and costs reported by vendor to MSE

(a) Monitoring well locations inside and outside the resistive heating plot are shown in Figure 3-1. Soil coring locations are shown in Figures 4-2 (pre-demonstration) and 4-3 (post-demonstration).

(b) Perimeter wells are PA-2, PA-10, IW-17, PA-15, and PA-7. Distant wells PA-1, PA-8, and PA-11, as well as other wells in the vicinity were sampled for various parameters, based on ongoing data acquisition and interpretation during the demonstration.

variability observed in the TCE concentrations in soil cores collected during preliminary site characterization in February 1999, a systematic unaligned sampling approach was used to divide the plot into a 4 × 3 grid and collect one soil core in each grid cell for a total of 12 soil cores (soil cores SB-1 to SB-12 in Figure 4-2) as described in the QAPP (Battelle, 1999d). The resulting 12 cores provided good spatial coverage of the 75-ft × 50-ft resistive heating plot and included two cores inside the Engineering Support Building. For each soil core, the entire soil column from ground surface to aquitard was sampled and analyzed in 2-ft sections. Another set of 12 cores was similarly collected after the demonstration. The soil boring locations are shown as SB-201 to SB-212 in Figure 4-3. Each sampling event, therefore, consisted of nearly 300 soil samples (12 cores, 23 2-ft intervals per core, plus duplicates). The line of dashes in Figures 4-2 and 4-3 represents the pre-demonstration DNAPL source boundary. This boundary includes all the soil coring locations where at least one of the pre-demonstration soil samples (depth intervals) showed TCE levels above 300 mg/kg.

An additional 12 soil cores were collected outside the plot, towards the end of the resistive heating application, before the post-demonstration monitoring. The objective of these cores was to determine if there had been significant migration of TCE and DNAPL outside the resistive heating plot. These coring locations are also shown in Figure 4-3.

Soil coring, sampling, and extraction methods are described in Appendix A.2 and summarized in this section. Figures 4-4 and 4-5 show the outdoor and indoor rigs used for soil coring outside and inside the Engineering Support Building. A direct-push rig with a 2-inch-diameter, 4-ft-long sample barrel was used for coring. As soon as the sample barrel was retrieved, the 2-ft section of core was split vertically and approximately one-quarter of the core (approximately 200 g of wet soil) was deposited into a predetermined volume (250 mL) of methanol for extraction in the field. The methanol extract was transferred into 20-mL volatile organic analysis (VOA) vials, which were shipped to a certified laboratory for analysis. The sampling and extraction technique used at this site provided better coverage of a heterogeneously distributed contaminant distribution as compared to the more conventional method of collecting and analyzing small soil samples at discrete depths, because the entire vertical depth of the soil column at the coring location could be analyzed. Preliminary site characterization had showed that the vertical variability of the TCE distribution

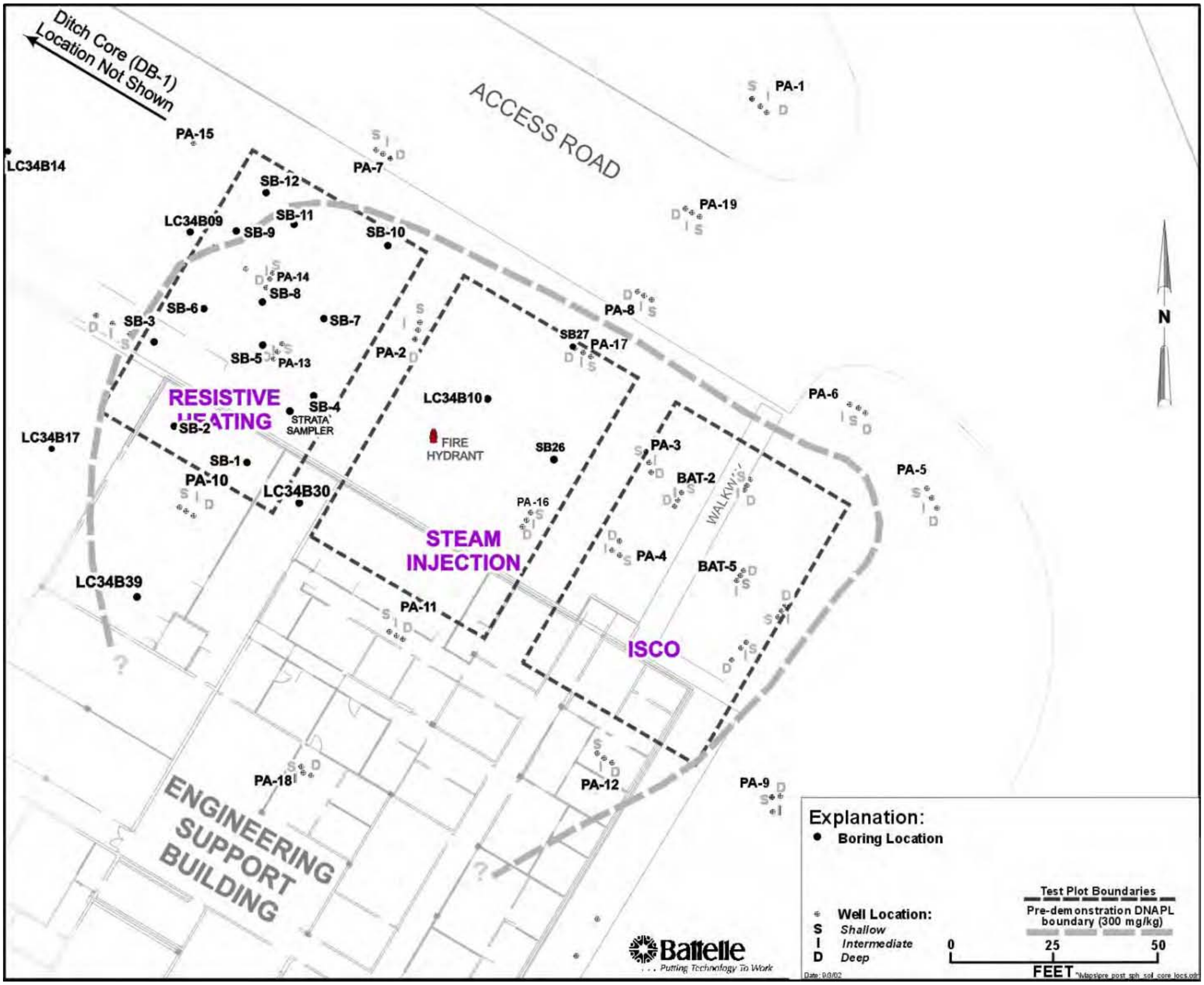

Figure 4-2. Pre-Demonstration Soil Coring Locations (SB-1 to SB-12) in Resistive Heating Plot (June 1999)

was greater than the horizontal variability, and this sampling and extraction method allowed continuous vertical coverage of the soil column.

One challenge during post-demonstration soil coring in the resistive heating plot was handling hot cores. The following steps were taken to minimize CVOC losses due to volatilization:

- Post-demonstration coring was delayed until all parts of the plot were below 90°C and steaming had stopped.
- As soon as the soil core barrel was withdrawn, both ends were capped and the barrel was dipped in an ice bath until the core had cooled to ambient temperature. The core barrel was kept in the ice bath long enough to cool the cores without breaking the seals at the capped ends (due to contraction of the barrel metals).

The efficiency of TCE recovery by this soil core processing method (modified EPA Method 5035; see Appendix A.2) was evaluated through a series of surrogate spike tests conducted for the demonstration (see Appendix G). In these tests, a surrogate compound (trichloroethane [TCA]) was spiked into soil cores from the Launch Complex 34 aquifer, extracted, and analyzed. The surrogate was spiked into separate soil cores both before and after

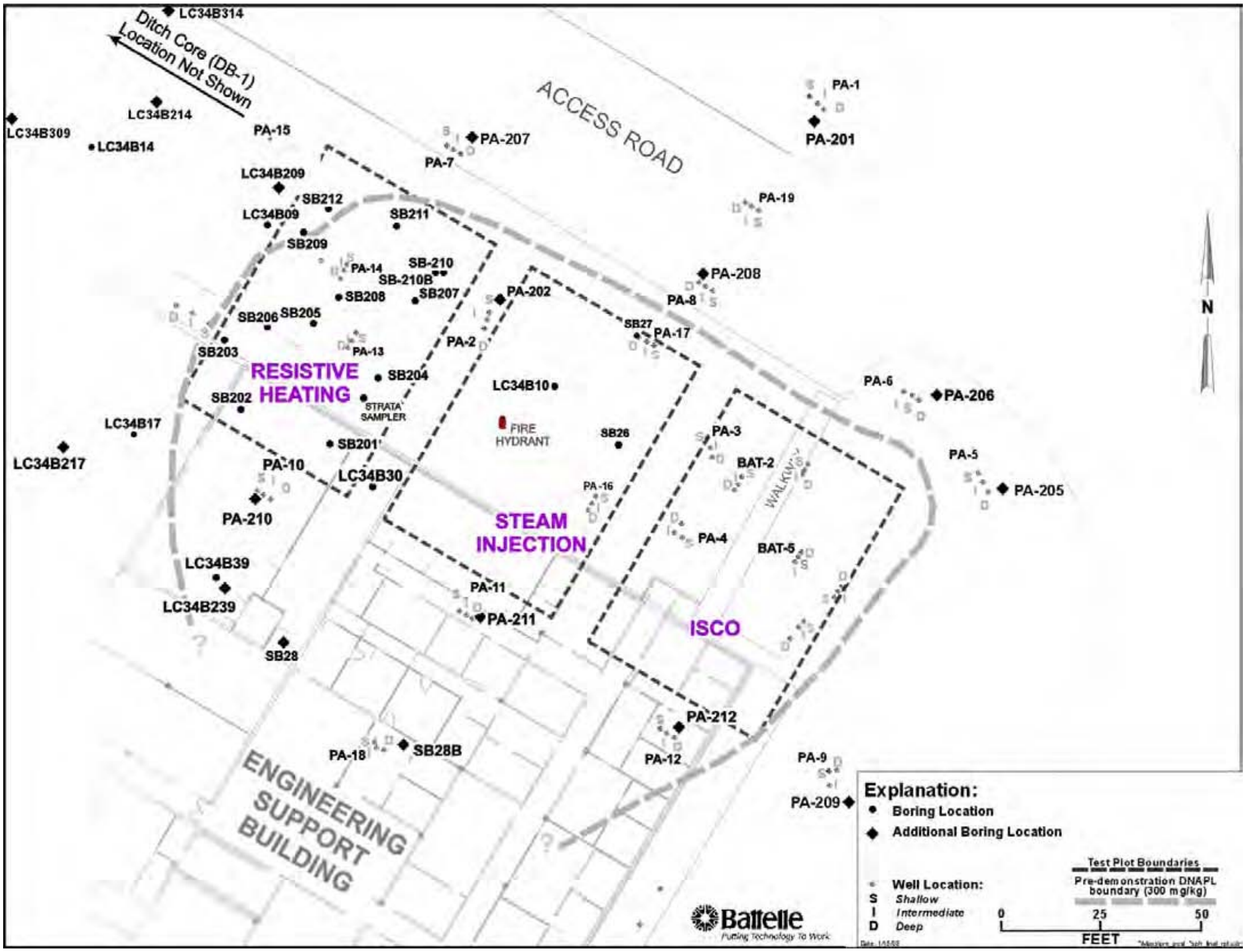

Figure 4-3. Post-Demonstration Soil Coring Locations (SB-201 to SB-212) in Resisitve Heating Plot (December 2000); Additional Soil Coring Locations Around Resistive Heating Plot (August-December 2000)

cooling to determine both the level of any volatilization losses from the core and the efficiency of extraction of the surrogate from the soil. Replicate extractions and analysis of a spiked surrogate (TCA) indicated a CVOC recovery efficiency between 84 and 113% (with an average recovery of 92%), which was considered sufficiently accurate for the demonstration (see Section 6 on Quality Assurance).

Two data evaluation methods were used for estimating TCE-DNAPL mass removal in the resistive heating plot: linear interpolation (or contouring), and kriging. The spatial variability or spread of the TCE distribution in a DNAPL source zone typically is high, because small pockets of residual solvent may be distributed unevenly across the source region. The two methods address this spatial variability in different ways, and therefore the resulting mass removal estimates differ slightly. Because it is impractical to sample every single point in the resistive heating plot and obtain a true TCE mass estimate for the plot, both methods basically address the practical difficulty of estimating the TCE concentrations at unsampled points by interpolating (estimating) between sampled points. The objective in both methods is to use the information from a limited sample set to make an inference about the entire population (the entire plot or a stratigraphic unit).

4.1.1 Linear Interpolation

Linear interpolation (or contouring) is the most straightforward and intuitive method for estimating TCE concentration or mass in the entire plot, based on a limited number of sampled points. TCE concentrations are

Figure 4-4. Outdoor Cone Penetrometer Test Rig for Soil Coring at Launch Complex 34

assumed to be linearly distributed between sampled points. A software program, such as EarthVision™, has an edge over manual calculations in that it is easier to conduct the linear interpolation in three dimensions. In contouring, the only way to address the spatial variability of the TCE distribution is to collect as large a number of samples as is practical so that good coverage of the plot is obtained; the higher the sampling density, the smaller the distances over which the data need to be interpolated. Nearly 300 soil samples were collected from the 12 coring locations in the plot during each event (pre-demonstration and post-demonstration), which was the highest number practical for this project. Appendix A.1 describes how the number and distribution of these sampling points were determined to obtain good coverage of the plot. The contouring software EarthVision™ takes the same methodology that is used for plotting water-level contour maps based on water-level measurements at discrete locations in a region. The only difference with this software is that the TCE concentrations are mapped in three dimensions to generate isoconcentration shells. The TCE concentration in each shell is multiplied by the volume of the shell (as estimated by the volumetric package in the software) and the bulk density of the soil (1.59 g/cm^3, estimated during preliminary site characterization) to estimate a mass for each shell. The TCE mass in each region of interest (Upper Sand Unit, Middle Fine-Grained Unit, Lower Sand Unit, and the entire plot) is obtained by adding up the portion of the shells contained in that region. The DNAPL mass is obtained by adding up the masses in only those shells that have TCE concentrations above 300 mg/kg. Contouring provides a single mass estimate for the region of interest.

Figure 4-5. Indoor Vibra-Push Rig (LD Geoprobe® Series) Used in the Engineering Support Building

4.1.2 Kriging

Kriging is a geostatistical interpolation tool that takes into consideration the spatial correlations among the TCE data in making inferences about the TCE concentrations at unsampled points. Spatial correlation analysis determines the extent to which TCE concentrations at various points in the plot are similar or different. Generally, the degree to which TCE concentrations are similar or different is a function of distance and direction. Based on these correlations, kriging determines how the TCE concentrations at sampled points can be optimally weighted to infer the TCE concentrations/masses at unsampled points in the plot or the TCE mass in an entire region of interest (entire plot or stratigraphic unit). Kriging accounts for the uncertainty in each point estimate by calculating a standard error for the estimate. Therefore, a range of TCE mass estimates is obtained instead of a single estimate; this range is defined by an average and a standard error or by a confidence interval. The confidence or level of significance required by the project objectives determines the width of this range. A level of significance of 0.2 (or 80% confidence) was determined as desirable at the beginning of the demonstration (Battelle, 1999d).

4.1.3 Interpreting the Results of the Two Mass Estimation Methods

The two methods address the spatial variability of the TCE distribution in different ways and, therefore, the resulting mass removal estimates differ slightly between the two methods. This section discusses the implication of these differences.

In both linear interpolation and kriging, TCE mass removal is accounted for on an absolute basis; higher mass removal in a few high-TCE concentration portions of the plot can offset low mass removal in other portions of the plot to infer a high level of mass removal. Kriging probably provides a more informed inference of the TCE mass removal because it takes into account the spatial correlations in the TCE distribution and the uncertainties (errors) associated with the estimates. At the same time, because a large number of soil samples were collected during each event, the results in Section 5.1 show that linear interpolation was able to overcome the spatial variability to a considerable extent and provide mass estimates that are close to the ranges provided by kriging.

4.2 Evaluating Changes in Aquifer Quality

A secondary objective of the performance assessment was to evaluate any short-term changes in aquifer quality due to the treatment. Resistive heating may affect both the contaminant and the native aquifer characteristics. Pre- and post-demonstration measurements conducted to evaluate the short-term impacts of the technology application on the aquifer included:

- CVOC measurements in the ground water inside the resistive heating plot
- Field parameter measurements in the ground water
- Inorganic measurements (common cations and anions) in the ground water
- Geochemical composition of the aquifer
- TDS, TOC, and 5-day BOD in the ground water
- TOC measurements in the soil
- Hydraulic conductivity of the aquifer
- Microbial populations in the aquifer (See Figure 4-6 and Appendix E).

These measurements were conducted primarily in monitoring wells within the plot, but some measurements also were made in the perimeter and distant wells.

4.3 Evaluating the Fate of the TCE-DNAPL in the Test Plot

Another secondary objective was to evaluate the fate of the TCE in the plot due to the resistive heating application. Possible pathways (or processes) for the TCE removed from the plot include degradation (destruction of TCE) and migration from the resistive heating plot (to the surrounding regions). These pathways were evaluated by the following measurements:

Figure 4-6. Collecting and Processing Ground-Water Samples for Microbiological Analysis

- Chloride (mineralization of CVOCs leads to formation of chloride) and other inorganic constituents in ground water
- Hydraulic gradients (gradients indicative of ground-water movement)
- Potassium ion in the resistive heating plot and surrounding wells (potassium ion from potassium permanganate addition in the ISCO plot acts as a conservative tracer for tracking movement of injected solution)
- Surface emission tests were conducted as described in Appendix F to evaluate the potential for CVOC losses to the vadose zone and atmosphere (see the testing setup, Figure 4-7, and the map, Figure 5-29)
- CVOC concentrations in soil outside the resistive heating plot (vadose and saturated zones)

Figure 4-7. Surface Emissions Testing at Launch Complex 34

- CVOC concentrations in the Lower Clay Unit and semi-confined aquifer below the resistive heating plot.

4.3.1 Potential for Migration to the Semi-Confined Aquifer

During the week of April 2, 2001, Battelle installed three wells into the semi-confined aquifer with a two-stage (dual-casing) drilling and completion process with a mud rotary drill rig provided by Environmental Drilling Services, Inc., from Ocala, FL. Figure 4-8 shows the location of these wells (PA-20, PA-21, and PA-22). The objective of installing these deeper wells was to evaluate the potential presence of CVOC contamination in the semi-confined aquifer and to assess the effect of the DNAPL remediation demonstration on the semi-confined aquifer. These wells were first proposed in 1999, but the IDC and Battelle decided to forgo their construction because of NASA's concerns over breaching the thin aquitard (Lower Clay Unit). However, by early 2001, nonintrusive geophysical tests indicated the possibility of DNAPL in the semi-confined aquifer. It was not clear whether any DNAPL in the semi-confined aquifer would be related to the demonstration activities or not. However, the IDC and Battelle decided that there were enough questions about the status of the confined aquifer that it would be worthwhile to characterize the deeper aquifer. Suitable precautions would be taken to mitigate any risk of downward migration of contamination during the well installation.

WSRC sent an observer to monitor the field installation of the wells. The observer verified that the wells were

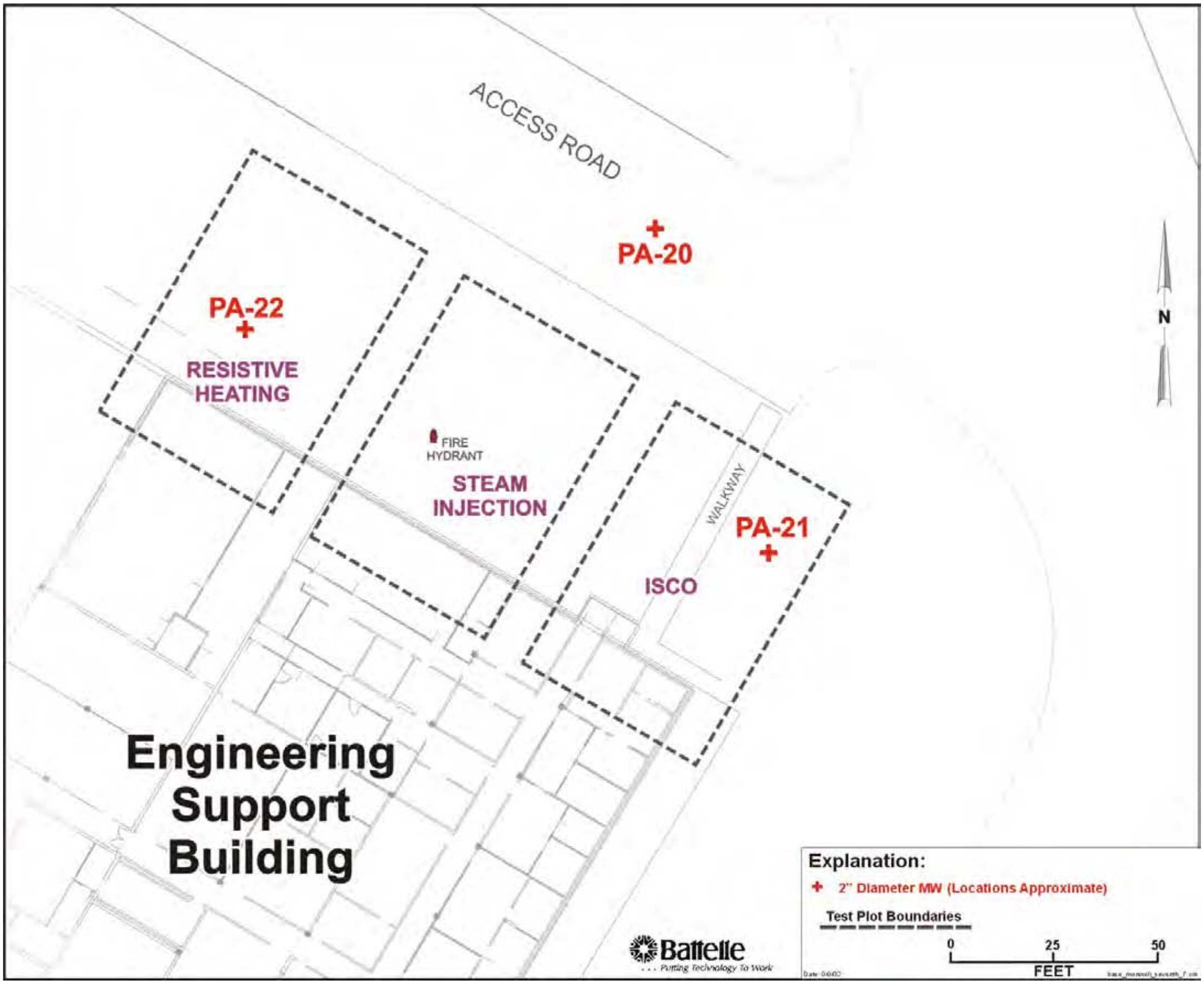

Figure 4-8. Location of Semi-Confined Aquifer Wells at Launch Complex 34

installed properly and that no drag-down of contaminants was created during their installation.

4.3.1.1 Geologic Background at Launch Complex 34

At the Launch Complex 34 area, there are several aquifers, reflecting a barrier island complex overlying coastal sediments (Figure 4-9). The surficial aquifer is comprised of layers of silty sand and shells, and includes the Upper Sand Unit, the Middle Fine-Grained Unit, and the Lower Sand Unit. It extends down to about 45 ft bgs, where the Lower Clay Unit (aquitard) is encountered. Previous logging suggested that the Lower Clay Unit is 3 ft thick and consists of gray clay with low to medium plasticity. A 40- to 50-ft-thick confined aquifer (Caloosahatchee Marl equivalent) resides under the Lower Clay Unit and is composed of silty to clayey sand and shells. As shown in Figure 4-9, Launch Complex 34 is situated just above the semi-confined aquifer in the Hawthorne Formation, which is a clayey sand-confining layer. The limestone Floridan Aquifer underlies the Hawthorne Formation and is a major source of drinking water for much of Florida. Table 4-2 summarizes the character and water-bearing properties of the hydrostratigraphic units in the area (Schmalzer and Hinkle, 1990).

4.3.1.2 Semi-Confined Aquifer Well Installation Method

Figure 4-10 shows the well completion diagram for the three semi-confined aquifer wells. In the first stage of well installation, a 10-inch borehole was advanced to about 45 ft bgs and completed with 6-inch blank stainless steel casing. The surface casing was advanced until it established a key between the “surface” casing and the Lower Clay Unit. The borehole was grouted around the surface casing. Once the grout around the 6-inch surface casing had set, in the second stage, a 5⅞-inch borehole was drilled through the inside of the surface casing to a depth of 61 ft bgs. A 2-inch casing with screen was advanced through the deeper borehole to set the well. This borehole also was grouted around the 2-inch casing. These measures were undertaken to prevent any DNAPL from migrating to the semi-confined aquifer. Figure 4-11 shows the surface casing and inner (screened well) casing for the dual-casing wells installed at Launch Complex 34. The detailed well installation method is as follows.

To verify the depth of the Lower Clay Unit, at each well location, a 3⅞-inch pilot hole first was installed to a depth of 40 ft using a tricone roller bit. After this pilot hole was drilled, split-spoon samples were collected in 2-ft (or 1-ft) intervals as soils were observed and logged in search of the top interface of the Lower Clay Unit or aquitard. Upon retrieval of a 2-ft split-spoon sample, the borehole was then deepened to the bottom of the previously spooned interval. Once the previously spooned interval was drilled, the drilling rods and bit were pulled out of the hole and replaced with a new split spoon that was driven another 2 ft ahead of the borehole. Standard penetration tests (i.e., blow counts) were conducted and

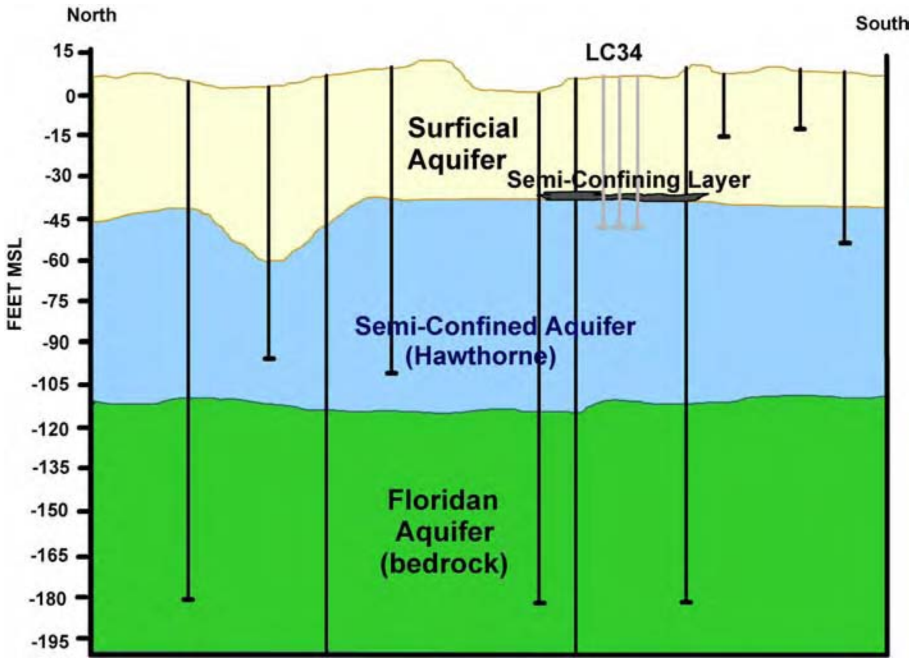

Figure 4-9. Regional Hydrogeologic Cross Section through the Kennedy Space Center Area (after Schmalzer and Hinkle, 1990)

Table 4-2. Hydrostratigraphic Units of Brevard Country, Florida[(a)]

Geologic Age	Stratigraphic Unit		Approximate Thickness (ft)	General Lithologic Character	Water-Bearing Properties
Recent (0.1 MYA-present)	Pleistocene and Recent Deposits		0-110	Fine to medium sand, coquina and sandy shell marl.	Permeability low due to small grain size, yields small quantities of water to shallow wells, principal source of water for domestic uses not supplied by municipal water systems.
Pleistocene (1.8-0.1 MYA)					
Pliocene (1.8-5 MYA)	Upper Miocene and Pliocene Deposits (Calooshatchee Marl)		20-90	Gray to greenish gray sandy shell marl, green clay, fine sand, and silty shell.	Permeability very low, acts as confining bed to artesian aquifer, produces small amount of water to wells tapping shell beds.
Miocene (5-24 MYA)	Hawthorne Formation		10-300	Light green to greenish gray sandy marl, streaks of greenish clay, phosphatic radiolarian clay, black and brown phosphorite, thin beds of phosphatic sandy limestone.	Permeability generally low, may yield small quantities of fresh water in recharge areas, generally permeated with water from the artesian zone. Contains relatively impermeable beds that prevent or retard upward movement of water from the underlying artesian aquifer. Basal permeable beds are considered part of the Floridan aquifer.
Eocene (37-58 MYA)	Ocala Group	Crystal River Formation	0-100	White to cream, friable, porous coquina in a soft, chalky, marine limestone.	Floridan aquifer: Permeability generally very high, yields large quantities of artesian water. Chemical quality of the water varies from one area to another and is the dominant factor controlling utilization. A large percentage of the ground water used in Brevard County is from the artesian aquifer. The Crystal River Formation will produce large quantities of artesian water. The Inglis Formation is expected to yield more than the Williston Formation. Local dense, indurate zones in the lower part of the Avon Park Limestone restrict permeability, but in general the formation will yield large quantities of water.
		Williston Formation	10-50	Light cream, soft, granular marine limestone, generally finer grained than the Inglis Formation, highly fossiliferous.	
		Inglis Formation	70+	Cream to creamy white, coarse granular limestone, contains abundant echinoid fragments.	
	Avon Park Limestone		285+	White to cream, purple tinted, soft, dense chalky limestone. Localized zones of altered to light brown or ashen gray, hard, porous, crystalline dolomite	

(a) Source: Schmalzer and Hinkle (1990).
MYA = million years ago.

Project #: G004065-31	Site: LC34, Cape Canaveral	Well #: PA-20/21/22
Drilling Contractor: EDS (SBC)	Rig Type and Drilling Method: Rotary	Date: 4/5/01
Reviewed By: S. Yoon	Driller: R. Hutchinson	Hydrologist: C. J. Perry

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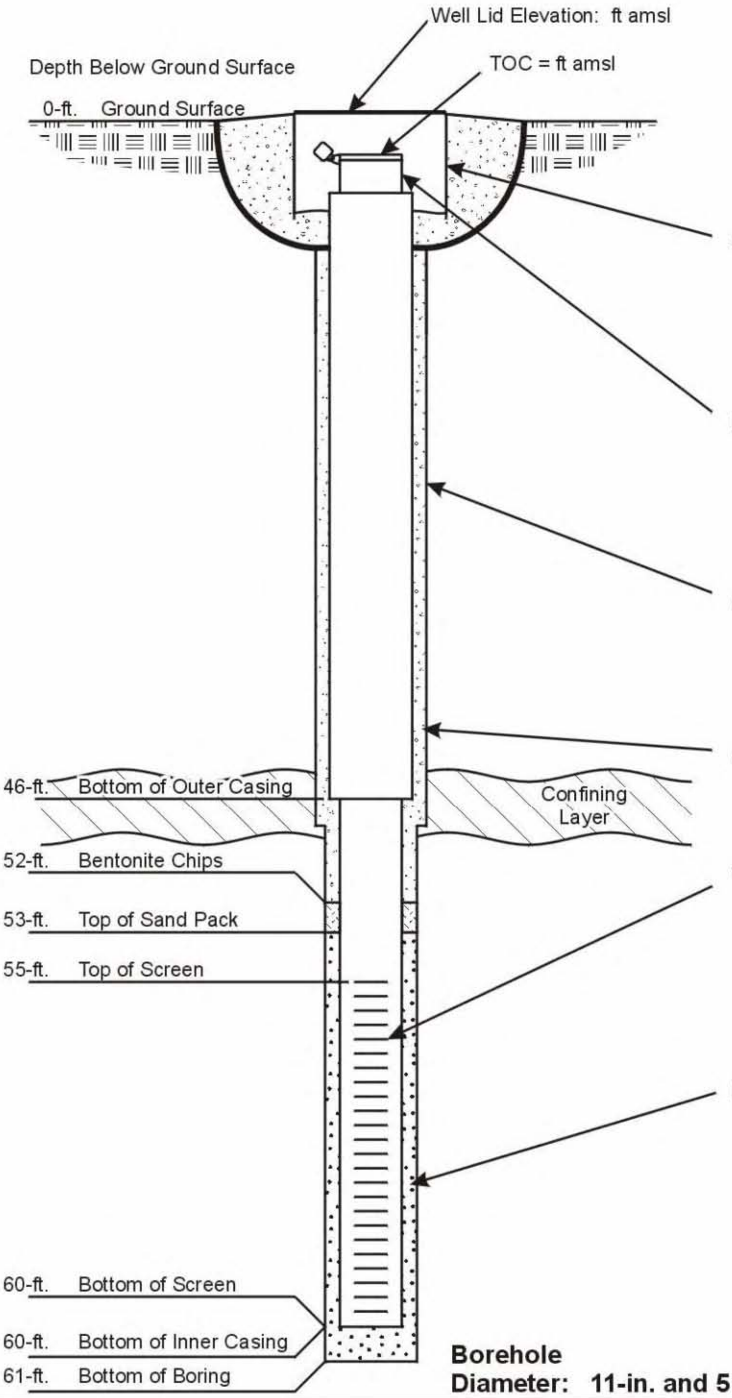


Surface Completion:
Size 7" 2'x2' Concrete Pad
Type Water Tight Well Cover
Well Cap Locking Well Cap

Inside Well Casing:
Type 304 SS SCH10
Diameter 2-in.
Amount 60-ft.-long section

Outer Well Casing:
Type 304 SS SCH10
Diameter 6-in.
Amount 46-ft.-long section

Grout:
Type Type G + 30% Silica Sand

Well Screen:
Type 304 SS SCH10
Amount 5-in.
Diameter 2-in.
Slot Size 0.010

Filter Pack:
Type #20/30 Sand

NOT TO SCALE

Borehole Diameter: 11-in. and 5 7/8-in.

WELGRM20.CDR

Figure 4-10. Well Completion Detail for Semi-Confined Aquifer Wells

Figure 4-11. Pictures Showing (a) Installation of the Surface Casing and (b) the Completed Dual-Casing Well

logged during each split-spoon advance. The blow counts were useful in identifying the soil types that are penetrated during spooning. They were also useful in helping to determine the exact interval of soil recovered from spoons that lacked total recovery. The split-spoon soil samples were logged. The soils were visually logged for soil type and description, photoionization detector (PID) scans were run, and at least one soil sample per 2-ft spoon interval was collected for methanol extraction and analysis.

Once the top portion (approximately the first 1.5 ft) of the Lower Clay Unit was retrieved by split spoons in each borehole, the spoon and rods were pulled out of the borehole and the hole was reamed with a 10-inch tricone rotary drill bit to the depth of the lowest spooned interval. Before the 6-inch-diameter casing was set in the hole, a polyvinyl chloride (PVC) slipcap was placed on the bottom of the casing to keep it free of drilling mud and soil. Use of slipcaps was an added precaution to prevent any possibility of downward contamination. As the casing was lowered in the hole, it was filled with clean water to prevent it from becoming buoyant. When the casing was set to the drilled depth of about 45 ft, it was grouted in place.

After the grout was allowed to set for at least 24 hours, the split cap was drilled through with a 5⅞-inch roller bit. Then split-spoon sampling progressed through the remainder of the Lower Clay Unit and into the semi-confined aquifer. Split-spoon samples were collected totaling 4 ft of lifts before the hole was reamed with the 5⅞ bit as fresh drilling mud was circulated in the hole. Split spooning progressed to a depth of 60 ft. Each hole was reamed an extra foot, to 61 ft, before the screen and casing were set. A sand pack was tremied into place from total depth to 2 ft above the top of the well screen (about 53 ft bgs). A bentonite seal (placed as a slurry) was then tremied in around the sand pack before the remainder of the casing was tremie-grouted into place with a Type G cement and silica flour slurry.

Once the split-spoon samples showed that the Lower Clay Unit had been reached, the 6-inch-diameter surface casing was set and grouted into place with a Type G (heat-resistant) cement and silica flour grout slurry. The drilling mud used for advancing the boreholes consisted of a product called “Super Gel-X bentonite.” This powdered clay material was mixed with clean water in a mud pit that was set and sealed to the borehole beneath the drilling platform. The drilling mud was mixed to a density and viscosity that is greater than both ground water and the bulk density of soil. This mud was pumped down through the drill pipe, out through the drill bit, and then pushed upward (circulated) through the borehole annulus into the mud pit (open space between the drilling rods and borehole wall). Use of the mud stabilizes the borehole, even in sandy soils, enabling advancement of the borehole in depths well below the water table without heaving or caving. The mud seals the borehole walls, preventing the borehole from being invaded by ground water and contaminants. The mud also lifts all of the cuttings created by the drill bit as the hole is advanced. Once the drilling mud rose to the top of the annulus, it was captured in the mud pit where cuttings were removed by a series of baffles through which the mud was circulated.

The mud pit was monitored with a PID throughout the drilling process. At no time did the PID detect VOCs in the drilling mud, indicating that no significant levels of contamination were entering the borehole and being carried downward into cleaner aquifer intervals as the drilling advanced.

After each well was installed, it was developed using a 3-ft-long stainless steel bailer and a small submersible pump. Bailing was done to surge each well and lift the coarsest sediments. The submersible pump was then used to lift more fines that entered the well as development progressed. A total of at least three well volumes (approximately 27 gal) were lifted from each well. Ground-water sampling was performed following well development. Standard water quality parameters were measured during sampling, and ground-water samples were collected after these parameters became stable.

4.4 Verifying Resistive Heating Operating Requirements and Costs

Another secondary objective of the demonstration was to verify the vendor's operating requirements and cost for the technology application. The vendor prepared a detailed report describing the operating requirements and costs of the resistive heating application (CES, 2001). An operating summary based on this report is provided in Section 3.2. Costs of the technology application also were tracked by MSE, the DOE contractor who subcontracted the resistive heating vendor. Site characterization costs were estimated by Battelle and TetraTech EM, Inc.

5. Performance Assessment Results and Conclusions

The results of the performance assessment methodology outlined in Section 4 are described in this section.

5.1 Change in TCE-DNAPL Mass in the Plot

Section 4.1 describes the methodology used to estimate the masses of total TCE and DNAPL removed from the plot due to the resistive heating application at Launch Complex 34. Intensive soil sampling was the primary tool for estimating total TCE and DNAPL mass removal. Total TCE refers to both dissolved-phase and DNAPL TCE. DNAPL refers to that portion of total TCE in a soil sample that exceeds the threshold concentration of 300 mg/kg (see Section 2.3). Pre- and post-demonstration concentrations of TCE at 12 soil coring locations (nearly 300 soil samples) inside the resistive heating plot were tabulated and graphed to *qualitatively* identify changes in TCE-DNAPL mass distribution and efficiency of the resistive heating application in different parts of the plot (Section 5.1.1). In addition, TCE-DNAPL mass removal was *quantified* by two methods:

- Linear Interpolation (Section 5.1.2)
- Kriging (Section 5.1.3)

These quanititative techniques for estimating TCE-DNAPL mass removal due to the resistive heating application are described in Section 4.1; the results are described in Sections 5.1.2 through 5.1.4.

5.1.1 Qualitative Evaluation of Changes in TCE-DNAPL Distribution

Figure 5-1 charts the pre- and post-demonstration concentrations of TCE in the soil samples from the 12 coring locations in the resistive heating plot as shown in Figures 4-2 (pre-demonstration) and 4-3 (post-demonstration). This chart allows a simple numerical comparison of the pre- and post-demonstration TCE concentrations at paired locations. Colors in the chart indicate the represented soil color observed in each soil sample of 2-ft intervals during the soil sample collection. Gray and tan are natural colors observed above and below the ground-water table from Launch Complex 34 soil samples. The chart in Figure 5-1 shows that at several locations in the plot, TCE concentrations were considerably lower in all three units. The thicker horizontal lines in the chart indicate the depths at which the Middle Fine-Grained Unit was encountered at each location. As seen in Figure 5-1, the highest pre-demonstration contamination detected was under the Engineering Support Building in the deepest samples from soil cores SB-1 (37,537 mg/kg) and SB-2 (41,044 mg/kg).

Figures 5-2 to 5-4 show representative pre- and post-demonstration distributions of TCE in soil from the Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit in the resistive heating plot and surrounding aquifer. A graphical representation of the TCE data illustrates the areal and vertical extent of the initial contaminant distribution and the subsequent changes in TCE concentrations. The colors yellow to red indicate DNAPL (TCE >300 mg/kg). In general, the portions of the aquifer under or near the building (SB-201, SB-202, and SB-204) and along the eastern half of the plot (SB-207 and SB-208) had the highest pre-demonstration contamination generally occurring right on top of the Lower Clay Unit. The post-demonstration coring showed that the resistive heating process had caused a considerable decline in TCE concentrations in several parts of the resistive heating plot, especially in the Lower Sand Unit, which showed the sharpest declines in TCE-DNAPL concentrations. Access to the portion of the test plot under the building by the application of the resistive heating technology also appeared to be good, given that angled electrodes were inserted into this region from outside the building. Some portion of cores SB-201, SB-202, and SB-203, collected under and near the building, contained considerable post-demonstration concentrations of both total TCE and DNAPL. Figure 5-5 depicts three-dimensional (3-D) DNAPL distributions identified (based on the 300 mg/kg threshold or greater) during the pre- and post-demonstration sampling in the resistive heating plot. Most of the remaining DNAPL in the plot appears to be in and near the Middle Fine-Grained Unit.

Top Depth	Bottom Depth	Pre-Demo SB1	Post-Demo SB201	Pre-Demo SB2	Post-Demo SB202	Pre-Demo SB3	Post-Demo SB203	Pre-Demo SB4	Post-Demo SB204
0	2	8	0.8	NA	ND	9.2	1	ND	1
2	4	5	1.8	NA	ND	0.9	ND	4.6	3
4	6	0.3	2.9	1.7	2.9	0.1 J	1	5.1	ND
6	8	3	1.4	0.7	6.7	0.3 J	3	48.7	5
8	10	11	18	0.4 J	40.2	0.3 J	90	0.2 J	6
10	12	9	13	0.7	29.2	0.3 J	114	4.6	32
12	14	12	ND	ND	9.4	0.3 J	61	NA	NA
14	16	NA	ND	1.1	1.9	0.6	126	8.3	NA
16	18	4	NA	0.7	53	1.3	97	6.5	19
18	20	122	ND	2.5	111	1.0	71	6.0	2
20	22	315	28	2	4,295	8.9	NA	54.1	83
22	24	1,935	60	50	1,248	NA	NA	60	105
24	26	820	3,927	108	102	183	258	9,051	240
26	28	526	401	292	353	109	247	185	195
28	30	941	467	458	5,561	35	1,217	167	403
30	32	19,091	385	295	390	5	287	12,669	197
32	34	349	211	174	465	17	56	112	263
34	36	624	254	176	102	35.5 D	77	100	178
36	38	1,025	265	440	429	1.4 J	308	288	425
38	40	5,874	318	558	474	27	302	848	139
40	42	5,677	186	5	250	115	186	160	388
42	44	368	146	249	335	204	34	167	364
44	46	33,100	364	251	8	220	41	30,223	NA
46	48	37,537	270	41,044	NA	NA	NA	NA	NA

Figure 5-1. Distribution of TCE Concentrations (mg/kg) During Pre- and Post-Demonstration in the Resistive Heating Plot Soil (page 1 of 3)

Top Depth	Bottom Depth	*Pre-Demo SB5*	*Post-Demo SB205*	*Pre-Demo SB6*	*Post-Demo SB206*	*Post-Demo SB7*	*Post-Demo SB207*	*Pre-Demo SB8*	*Post-Demo SB208*
0	2	**ND**	**6**	**ND**	**6**	**0.6**	**ND**	**0.3 J**	**2**
2	4	**ND**	**1**	**ND**	**ND**	**0.1**	**0**	**0.2 J**	**1**
4	6	**ND**	**12**	**ND**	**6**	**ND**	**6**	**ND**	**5**
6	8	**ND**	**5**	**ND**	**3**	**ND**	**61**	**1.1**	**72**
8	10	**ND**	**10**	**ND**	**55**	**1.0**	**ND**	**0.5 J**	**ND**
10	12	**0.3 J**	**10**	**ND**	**69**	**0.0**	**ND**	**0.8**	**ND**
12	14	**ND**	**17**	**ND**	**71**	**ND**	**ND**	**1.2 J**	**24**
14	16	**ND**	**122**	**ND**	**76**	**0.2**	**1**	**342**	**6**
16	18	**ND**	**197**	**1.9**	**164**	**0.0**	**1**	**0.5 J**	**27**
18	20	**5.2**	**89**	**ND**	**119**	**10**	**ND**	**1.7**	**NA**
20	22	**27.7**	**61**	**3.9**	**224**	**31**	**58**	**217**	**33**
22	24	**1,835**	**NA**	**18.6**	**135**	**NA**	**85**	**329**	**12**
24	26	**260**	**177**	**10.8**	**213**	**143**	**516**	**330**	**29**
26	28	**5,880**	**177**	**69.1**	**235**	**330**	**367**	**184**	**31**
28	30	**542**	**102**	**54.6**	**105**	**140**	**186**	**182**	**34**
30	32	**902**	**150**	**17.0**	**86**	**125**	**196**	**157**	**NA**
32	34	**5,345**	**140**	**17.5**	**63**	**91**	**389**	**294**	**52**
34	36	**23,362**	**64**	**11.4**	**35**	**139**	**403**	**113**	**63**
36	38	**8,062**	**146**	**20.5**	**99**	**260**	**159**	**141**	**2**
38	40	**28,168**	**236**	**11.2**	**89**	**113**	**82**	**NA**	**11**
40	42	**6,534**	**97**	**18.8**	**149**	**217**	**511**	**209**	**4**
42	44	**37,104**	**129**	**5.8**	**126**	**8,802**	**273**	**6,711**	**52**
44	46	**NA**	**NA**	**313.1**	**NA**	**NA**	**NA**	**NA**	**160**

Figure 5-1. Distribution of TCE Concentrations (mg/kg) During Pre- and Post-Demonstration in the Resistive Heating Plot Soil (page 2 of 3)

Top Depth	Bottom Depth	*Pre-Demo SB9*	*Post-Demo SB209*	*Pre-Demo SB10*	*Post-Demo SB210*	*Post-Demo SB210B*	*Pre-Demo SB11*	*Post-Demo SB211*	*Pre-Demo SB12*	*Post-Demo SB212*
0	2	**ND**	**ND**	**ND**	**ND**	**3**	**4.1**	**6**	**ND**	**ND**
2	4	**0.9**	**ND**	**ND**	**ND**	**2**	**2.8**	**2**	**ND**	**3**
4	6	**ND**	**4**	**ND**	**3**	**23**	**2.1**	**3**	**ND**	**10**
6	8	**ND**	**5**	**3.9**	**26**	**20**	**2.7**	**49**	**NA**	**12**
8	10	**6.5**	**1**	**2.8**	**NA**	**NA**	**0.7**	**1**	**ND**	**16**
10	12	**0.5**	**1**	**ND**	**NA**	**NA**	**1.1**	**NA**	**2.4**	**ND**
12	14	**ND**	**5**	**1.9**	**ND**	**ND**	**ND**	**ND**	**0.4 J**	**1**
14	16	**0.8**	**4**	**ND**	**6**	**ND**	**1.2**	**NA**	**ND**	**1**
16	18	**0.4**	**13**	**ND**	**NA**	**1**	**1.6**	**2**	**NA**	**ND**
18	20	**5**	**3**	**0.7**	**10**	**6**	**ND**	**3**	**ND**	**5**
20	22	**14**	**28**	**30.9**	**90**	**16**	**9.2**	**14**	**15.3**	**4**
22	24	**29**	**34**	**92.4**	**46**	**49**	**NA**	**8**	**40.1**	**6**
24	26	**26**	**64**	**106**	**265**	**569**	**94**	**4**	**112.1**	**20**
26	28	**84**	**36**	**98**	**117**	**310**	**167**	**13**	**256.9**	**10**
28	30	**30**	**28**	**40.3**	**170**	**77**	**49**	**319**	**29.6**	**7**
30	32	**2.5**	**11**	**4.8**	**287**	**27**	**43.7**	**102**	**2.2**	**3**
32	34	**ND**	**NA**	**ND**	**209**	**344**	**21.4**	**79**	**0.4**	**23**
34	36	**1.4**	**5**	**ND**	**428**	**315**	**2.0**	**71**	**0.2 J**	**1**
36	38	**ND**	**74**	**ND**	**264**	**124**	**0.0**	**14**	**0.7**	**3**
38	40	**3.4**	**54**	**13.9**	**242**	**219**	**0.4**	**9**	**0.5 J**	**ND**
40	42	**51**	**77**	**12.6**	**257**	**236**	**36.0**	**2**	**16.1**	**1**
42	44	**67**	**52**	**25.4**	**101**	**297**	**46.0**	**ND**	**36.5**	**2**
44	46	**NA**	**NA**	**11.8**	**59**	**NA**	**NA**	**NA**	**1.5**	**8**

NA: Not available due to no recovery or no sample collection at the sample depth.
ND: Not detected.
Color in the chart represents the soil sample color observed during the soil sample collection.
Solid horizontal lines demarcate the Middle Fine-Grained Unit.

Figure 5-1. Distribution of TCE Concentrations (mg/kg) During Pre- and Post-Demonstration in the Resistive Heating Plot Soil (page 3 of 3)

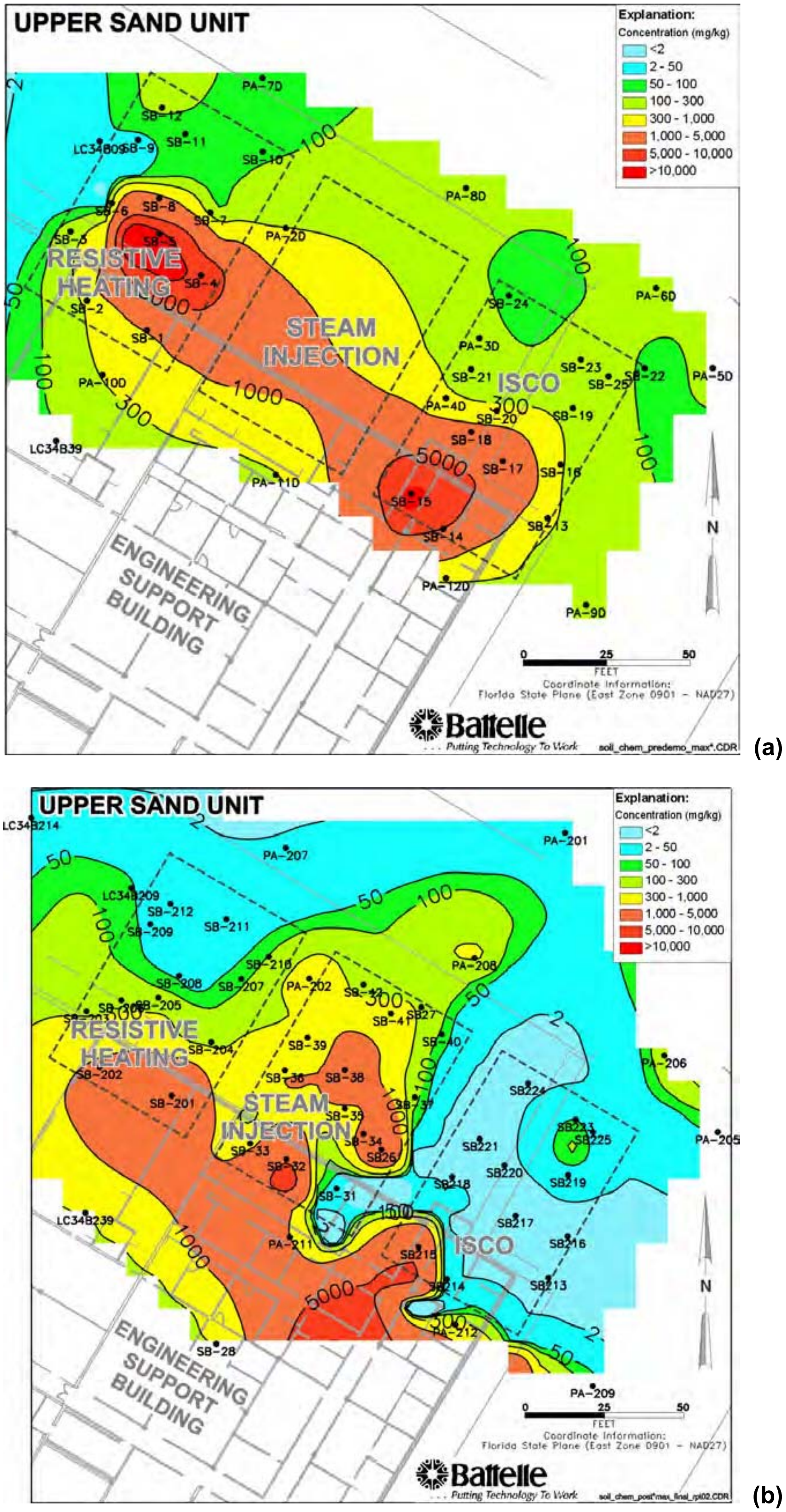


Figure 5-2. Representative (a) Pre-Demonstration (June 1999) and (b) Post-Demonstration (December 2000) Horizontal Cross Sections of TCE (mg/kg) in the Upper Sand Unit Soil

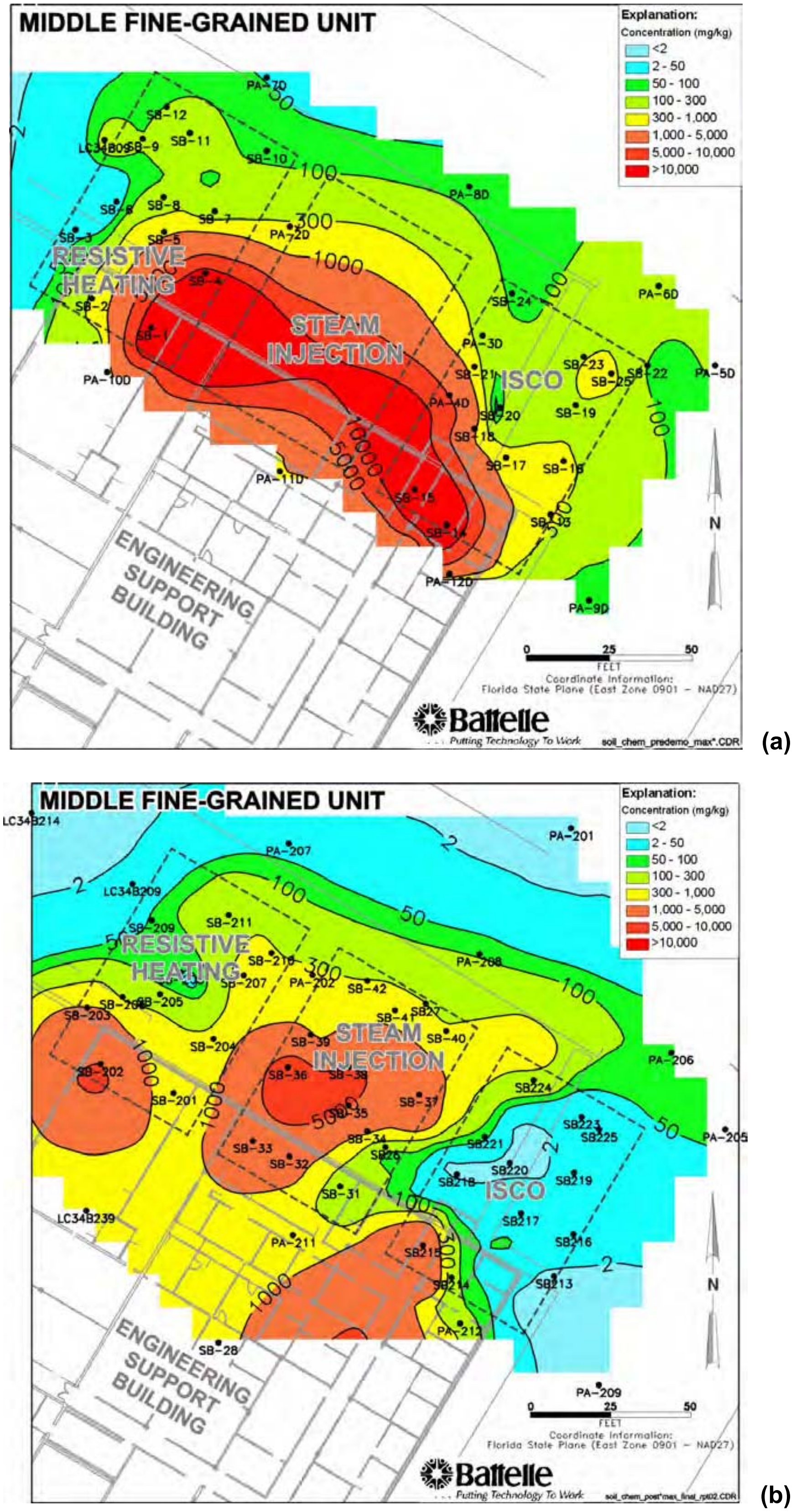


Figure 5-3. Representative (a) Pre-Demonstration (June 1999) and (b) Post-Demonstration (December 2000) Horizontal Cross Sections of TCE (mg/kg) in the Middle Fine-Grained Unit

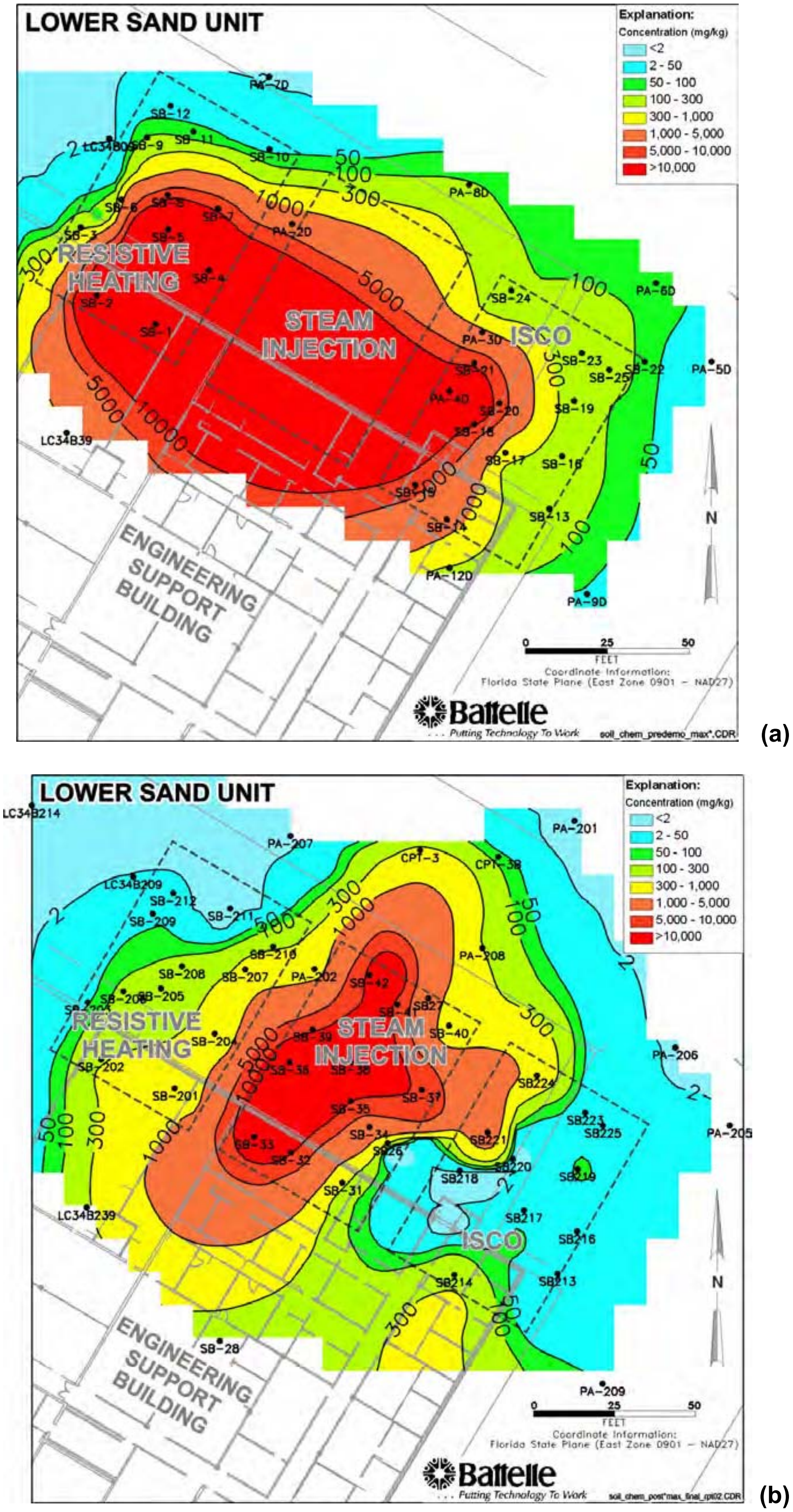


Figure 5-4. Representative (a) Pre-Demonstration (June 1999) and (b) Post-Demonstration (December 2000) Horizontal Cross Sections of TCE (mg/kg) in the Lower Sand Unit

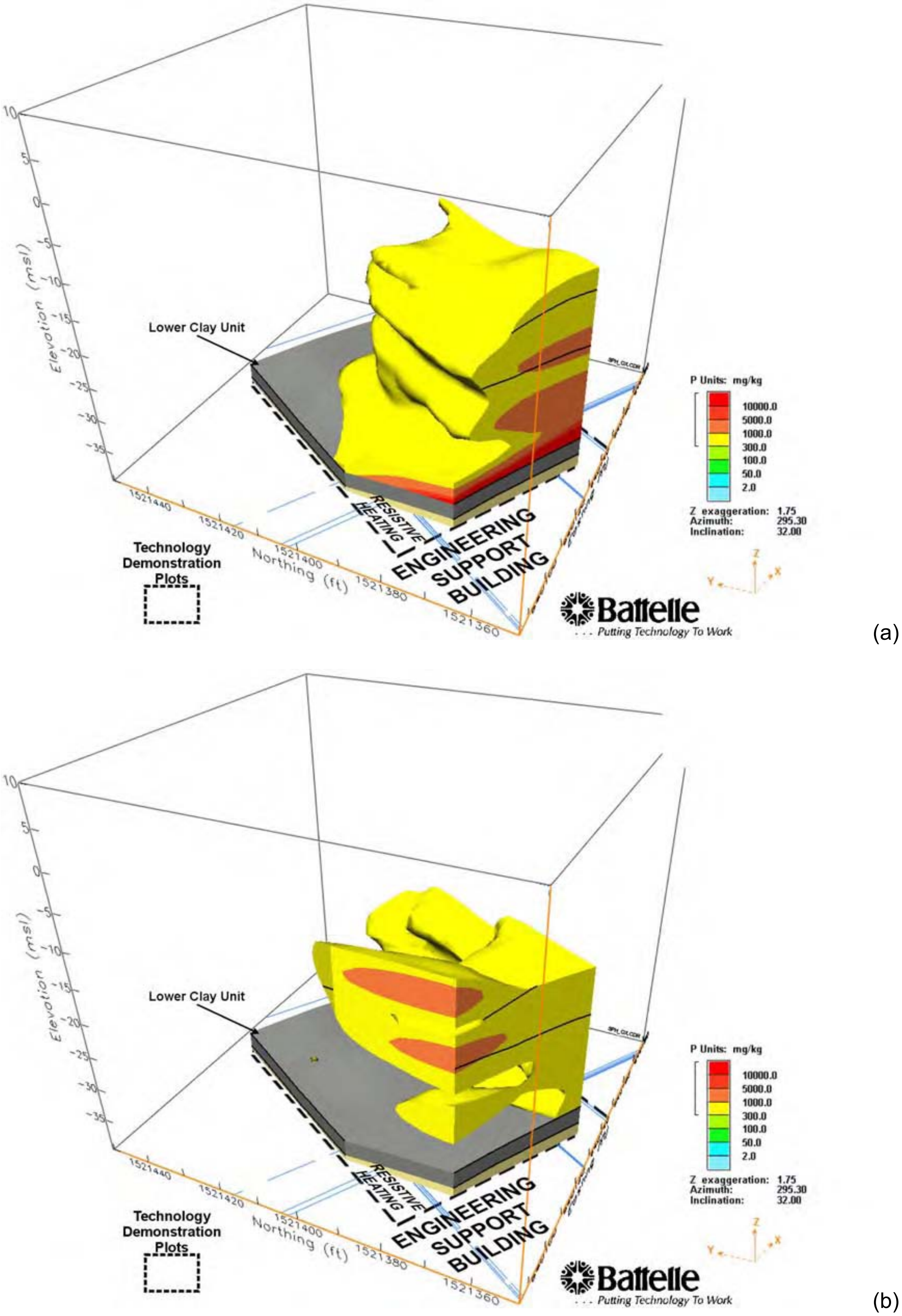


Figure 5-5. Three-Dimensional Distribution of DNAPL in the Resistive Heating Plot Based on (a) Pre-Demonstration (June 1999) and (b) Post-Demonstration (December 2000) Soil Sampling Events

This indicates that some TCE-DNAPL may have accumulated in or immediately above the Middle Fine-Grained Unit on its way up to the vadose zone and the vapor extraction system.

Figures 5-6 to 5-8 show the post-demonstration distribution of temperature of the aquifer in the shallow, intermediate, and deep wells in the Launch Complex 34 aquifer, as measured by existing thermocouples installed in the plot and by a downhole thermocouple in May 2000, toward the end of the resistive heating application and after electrode modifications had been made to improve heating efficiency (see Section 3.2.2). The temperature levels in the monitoring wells are a measure of the aquifer, although the absolute temperatures in the aquifer are probably slightly higher than in the wells. These figures show that all three layers — shallow, intermediate, and deep — eventually were heated well and probably achieved the desired boiling temperatures during the demonstration. These temperature measurements (in the monitoring wells) correspond well with the temperature measurements conducted by the vendor using thermocouples embedded in the test plot soil (CES, 2001).

In summary, a qualitative examination of the TCE-DNAPL and temperature data indicate that the resistive heating treatment generally achieved the desired level of heating in most parts of the plot, even in the relatively low-permeability Middle Fine-Grained Unit. The resistive heating treatment also was able to access and heat those portions of the test plot (e.g., right above the aquitard and under the building) that would be considered difficult to remediate. Heating in the Upper Sand Unit was not very efficient at the beginning of the demonstration, but modifications made by the vendor to the electrodes subsequently improved heating.

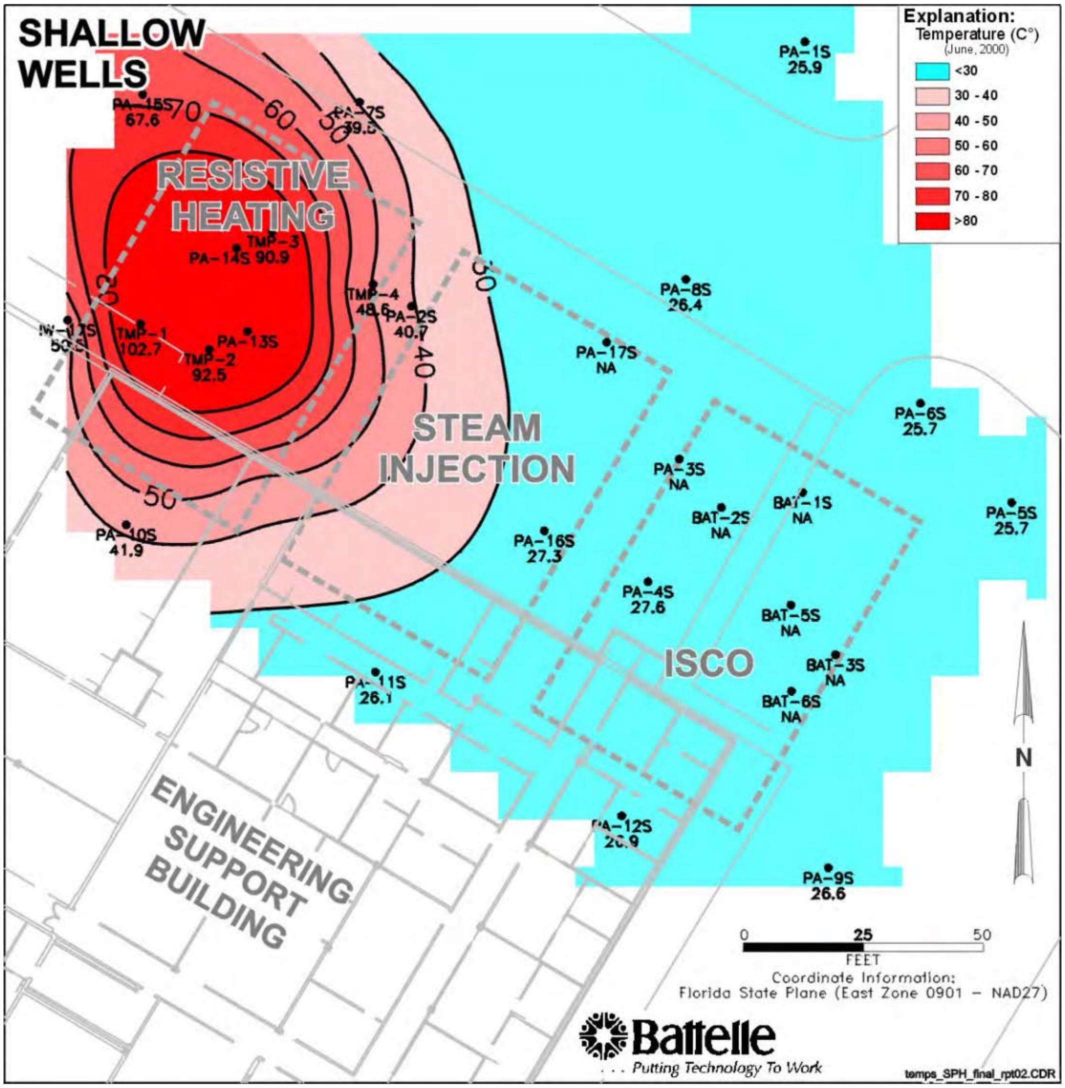


Figure 5-6. Distribution of Temperature in Shallow Wells near the Engineering Support Building at Launch Complex 34 (May 2000)

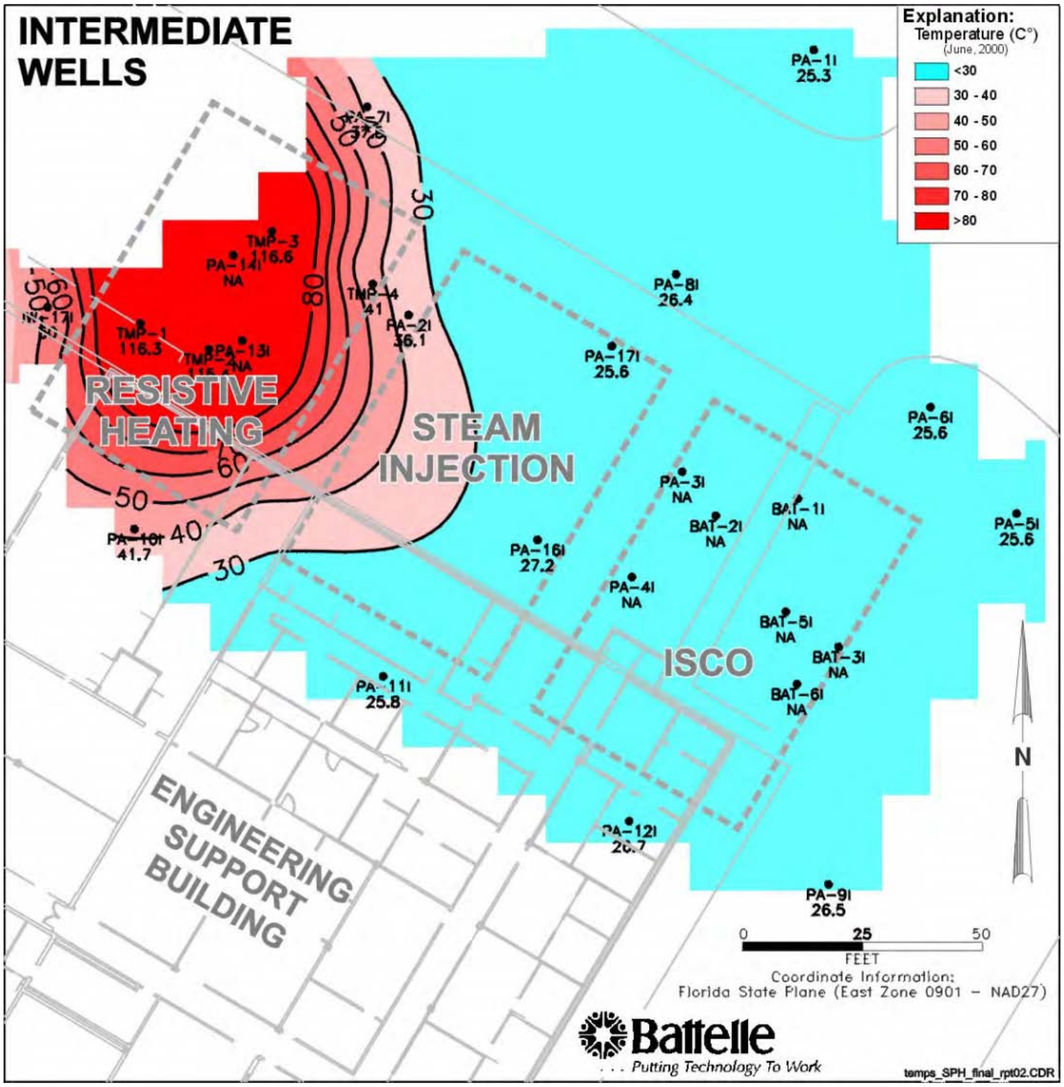


Figure 5-7. Distribution of Temperature in Intermediate Wells near the Engineering Support Building at Launch Complex 34 (May 2000)

5.1.2 TCE-DNAPL Mass Estimation by Linear Interpolation

Section 4.1.1 describes the use of contouring to estimate pre- and post-demonstration TCE-DNAPL masses and calculate TCE-DNAPL mass changes within the plot. In this method, EarthVision™, a three-dimensional contouring software, is used to group the TCE concentration distribution in the resistive heating plot into three-dimensional shells (or bands) of equal concentration. The concentration in each shell is multiplied by the volume of the shell and the bulk density of the soil to arrive at the TCE mass in that shell. The masses in the individual shells are added up to arrive at a TCE mass for the entire plot; this process is conducted separately for the pre- and post-demonstration TCE distributions in the resistive heating plot. The pre-demonstration TCE-DNAPL mass in the entire plot then can be compared with the post-demonstration mass in the entire plot to estimate the change in TCE-DNAPL mass in the plot. The results of this evaluation are described in this section.

Table 5-1 presents the estimated masses of total TCE and DNAPL in the resistive heating plot and the three individual stratigraphic units. Under pre-demonstration conditions, soil sampling indicated the presence of 11,313 kg of total TCE (dissolved and free phase), approximately 10,490 kg of which was DNAPL based on the 300 mg/kg of DNAPL criterion. Following the demonstration, soil sampling indicated that 1,101 kg of total TCE remained in the plot; approximately 338 kg of this remnant TCE was DNAPL. Therefore, the overall mass removal indicated by contouring was 90% of total TCE and 97% of DNAPL.

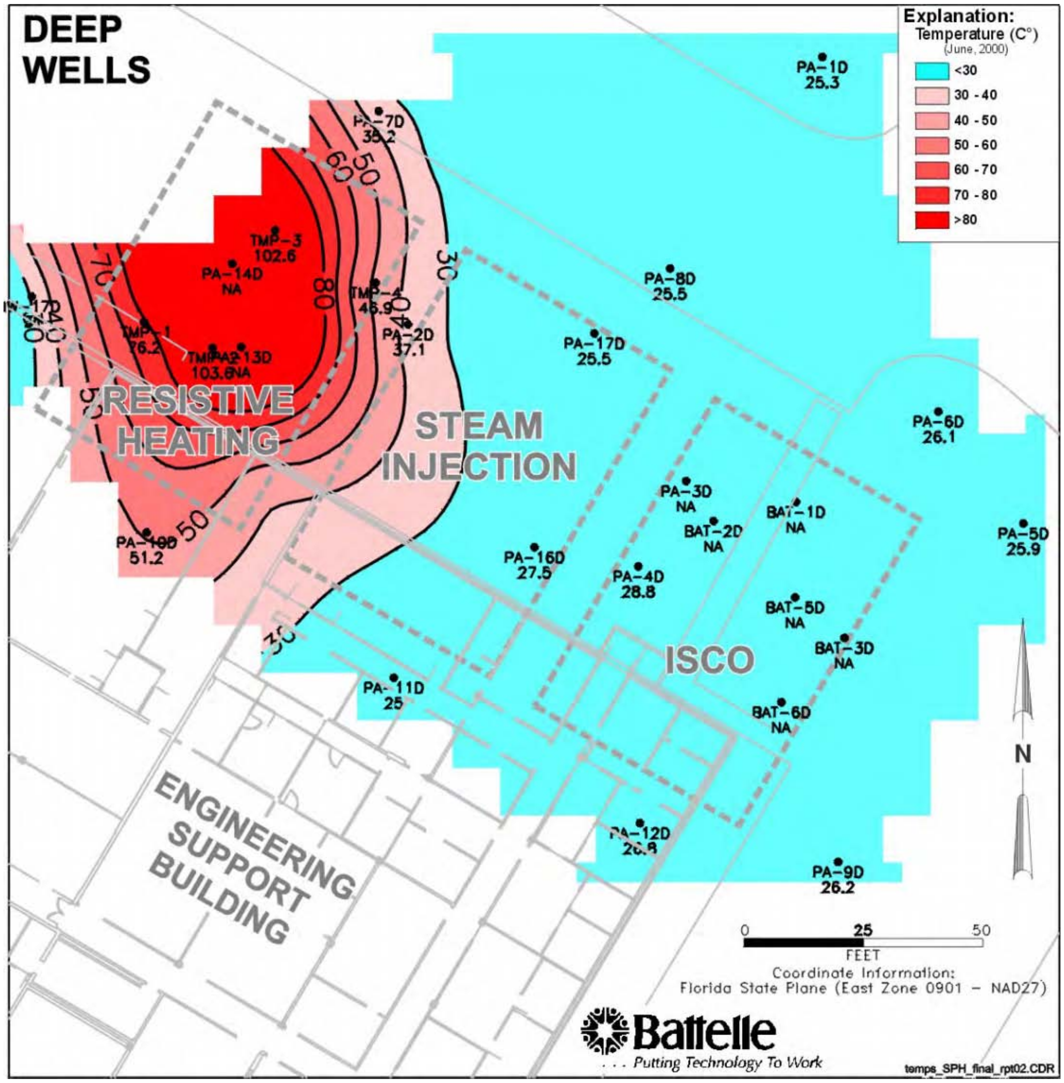


Figure 5-8. Distribution of Temperature in Deep Wells near the Engineering Support Building at Launch Complex 34 (May 2000)

Table 5-1 indicates that the highest mass removal (94% of total TCE and 98% of DNAPL) was achieved in the Lower Sand Unit, followed by the Middle Fine-Grained Unit. The removal efficiency appears to be substantially lower in the Upper Sand Unit, where heating was not as efficient (see Section 3.2.2) as in the deeper units. Because more than 90% of the pre-demonstration DNAPL mass resided in the Lower Sand Unit, the greater efficiency of removal in this unit was the driving factor behind the high removal percentage in the entire plot.

Table 5-1. Estimated Total TCE and DNAPL Mass Removal by Linear Interpolation of the TCE Distribution in Soil

	Pre-Demonstration		Post-Demonstration		Change in Mass (%)	
Stratigraphic Unit	Total TCE Mass (kg)	DNAPL Mass (kg)	Total TCE Mass (kg)	DNAPL Mass (kg)	Total TCE	DNAPL
Upper Sand Unit	183	70	141	35	–23	–50
Middle Fine-Grained Unit	611	447	304	124	–50	–72
Lower Sand Unit	10,519	9,973	656	179	–94	–98
Total (Entire Plot)	**11,313**	**10,490**	**1,101**	**338**	**–90**	**–97**

5.1.3 TCE Mass Estimation by Kriging

Section 4.1.2 describes the use of kriging to estimate the pre- and post-demonstration TCE masses in the aquifer. Whereas the contouring method linearly interpolates the TCE measurements at discrete sampling points to estimate TCE concentrations at unsampled points in the plot, kriging takes into account the spatial variability and uncertainty of the TCE distribution when estimating TCE concentrations (or masses) at unsampled points. Consequently, kriging provides a range of probable values rather than single TCE concentration estimates. Kriging is a good way of obtaining a global estimate (for one of the three stratigraphic units or the entire plot) for the parameters of interest (such as pre- and post-demonstration TCE masses), when the parameter is heterogeneously distributed.

Appendix A.1.2 contains a description of the application and results of kriging the TCE distribution in the resistive heating plot. Table 5-2 summarizes the total TCE mass estimates obtained from kriging. This table contains an average and range for each global estimate (Upper Sand Unit, Middle Fine-Grained Unit, Lower Sand Unit, and the entire plot total). Limiting the evaluation to DNAPL instead of total TCE limits the number of usable data points to those with TCE concentrations greater than 300 mg/kg. To avoid using too few data points (especially for the post-demonstration DNAPL mass estimates), kriging was conducted on total TCE values only.

The pre- and post-demonstration total TCE mass ranges estimated from kriging match the total TCE obtained from contouring relatively well, probably because the high sampling density (almost 300 soil samples in the plot per event) allows contouring to capture much of the variability of the TCE distribution in the plot. Kriging shows that the estimated decrease in TCE mass in the plot due to the resistive heating application is between 80 and 93% (89% on average). The decrease in TCE mass was highest in the Lower Sand Unit, followed by the Middle Fine-Grained Unit. The positive mass change numbers for the Upper Sand Unit indicate that the TCE mass in this unit may have increased. The Upper Sand Unit was not as efficiently heated as the other two units (see Section 3.2.2) and this may have caused upward-migrating TCE vapors to condense near the water table. An interesting observation from Table 5-2 is that the estimated ranges for the pre- and post-demonstration TCE masses do not overlap at all, either for the entire plot or for the Lower Sand or Middle Fine-Grained units; this indicates that the mass removal by the resistive heating application is significant at the 80% confidence level. The estimated decrease in TCE mass in the plot due to the resistive heating application is at least 80%.

The mass removal estimates obtained in the resistive heating plot by the two methods (linear interpolation and kriging) are consistent. Confidence intervals were not calculated for DNAPL removal from the individual units because an even smaller subset of samples (only those samples with TCE greater than 300 mg/kg) would be involved.

5.1.4 Summary of Changes in the TCE-DNAPL Mass in the Plot

In summary, the evaluation of TCE concentrations in soil indicates the following:

- In the horizontal plane, the highest pre-demonstration DNAPL contamination was under the Engineering Support Building and in the eastern half of the resistive heating plot.
- In the vertical plane, the highest pre-demonstration DNAPL contamination was immediately above the Lower Clay Unit.
- Linear interpolation of the pre- and post-demonstration TCE-DNAPL soil concentrations shows that the estimated pre-demonstration DNAPL mass in the resistive heating plot decreased by approximately 97% due to the heat application. Based on these estimates, the goal for 90% DNAPL mass removal was achieved.

Table 5-2. Estimated Total TCE Mass Removal by Kriging the TCE Distribution in Soil

	Pre-Demonstration Total TCE Mass[a]			Post-Demonstration Total TCE Mass			Change in Mass		
Stratigraphic Unit	**Average (kg)**	**Lower Bound (kg)**	**Upper Bound (kg)**	**Average (kg)**	**Lower Bound (kg)**	**Upper Bound (kg)**	**Average (%)**	**Lower Bound (%)**	**Upper Bound (%)**
Upper Sand Unit	168	90	247	310	176	443	84	393	–29
Middle Fine-Grained Unit	2,087	929	3,245	536	328	745	–74	–23	–90
Lower Sand Unit	9,332	5,411	13,253	437	391	483	–95	–91	–97
Total (Entire Plot)	**11,588**	**7,498**	**15,677**	**1,283**	**1,031**	**1,545**	**–89**	**–80**	**–93**

(a) Average and 80% confidence intervals (bounds).

- A statistical evaluation (kriging) of the pre- and post-demonstration TCE concentrations in soil shows that the estimated pre-demonstration total TCE mass in the resistive heating plot decreased between 80 and 93% due to the heat application. Total TCE includes both dissolved-phase TCE and DNAPL. The kriging results are generally consistent with the contouring results and indicate a high probability (80% confidence level) that the mass removal estimates are accurate.
- The estimated decrease in TCE-DNAPL mass in the plot was highest in the Lower Sand Unit, which contained the highest pre-demonstration TCE-DNAPL mass. Mass removal was especially good in difficult spots, such as immediately above the aquitard and under the Engineering Support Building.
- It is possible that some TCE-DNAPL accumulated in the Upper Sand Unit, immediately above the Middle Fine-Grained Unit, during the upward migration of the volatilized TCE. This possibility is discussed further in Section 5.3.2.

5.2 Changes in Aquifer Characteristics

This section describes the short-term changes in aquifer characteristics created by the resistive heating application at Launch Complex 34, as measured by monitoring conducted before, during, and immediately after the demonstration. The affected aquifer characteristics are grouped into four subsections:

- Changes in CVOC levels (see Appendix C for detailed results)
- Changes in aquifer geochemistry (see Appendix D for detailed results)
- Changes in the hydraulic properties of the aquifer (see Appendix B for detailed results)
- Changes in the aquifer microbiology (see Appendix E for detailed results).

Table 5-3 lists the pre- and post-demonstration levels of various ground-water parameters that are indicative of aquifer quality and the impact of the resistive heating treatment. Other important organic and inorganic aquifer parameters are discussed in the text. A separate microbiological evaluation of the aquifer is described in Appendix E.

5.2.1 Changes in CVOC Levels in Ground Water

Considerable DNAPL mass removed was expected to reduce CVOC levels in ground water, at least in the short term. Although influx from surrounding contamination is possible, it was not expected to contribute significantly to the post-demonstration sampling in the short term because of the relatively flat natural hydraulic gradient at the site. Therefore, CVOC levels were measured in the resistive heating plot wells before, during, and after the demonstration to evaluate short-term changes in CVOC levels in the ground water.

Appendix C tabulates the levels of TCE, *cis*-1,2-DCE, *trans*-1,2-DCE, and vinyl chloride in the ground water in the resistive heating plot wells. Figures 5-9 to 5-11 show dissolved TCE concentrations in the shallow, intermediate, and deep wells in the resistive heating plot and perimeter. Before the demonstration, several of the shallow, intermediate, and deep wells in the plot had concentrations close to the solubility of TCE (1,100 mg/L). Immediately after the demonstration, TCE concentrations in several of these wells (e.g., PA-13S, PA-13I, PA-14S and PA-14D) declined considerably, indicating that the treatment improved ground-water quality within the plot in the short term, whereas TCE concentrations in some of the monitoring wells (PA-7D and IW-17S) on the perimeter of the plot increased sharply.

The concentration of *cis*-1,2-DCE increased considerably in several wells (e.g., PA-13S, PA-13D, and PA-14S) within the plot. Although one well (PA-14D) showed a decline in *cis*-1,2-DCE levels, in general, there appears to have been some accumulation of *cis*-1,2-DCE in the plot. An increase in *cis*-1,2-DCE would indicate that some reductive dechlorination of TCE was taking place (biotically or abiotically). Recent research (Truex, 2003) has indicated heat-accelerated biodegradation of TCE to ethenes (acetylene, ethane, and ethene) at elevated temperatures. However, these byproducts were not evaluated for this demonstration of the resistive heating technology at Launch Complex 34. The possibility of TCE degradation is discussed further in Sections 5.3.1 and 5.3.2, but needs to be further evaluated. Vinyl chloride was not detected in several wells both before and after the demonstration, primarily because of the analytical limitations associated with samples containing higher levels of TCE.

5.2.2 Changes in Aquifer Geochemistry

The geochemical composition of both ground water and soil were examined to evaluate the effects of resistive heating application.

5.2.2.1 Changes in Ground-Water Chemistry

Among the field parameter measurements (tabulated in Appendix D) conducted in the affected aquifer before, during, and after the demonstration, the following trends were observed:

Table 5-3. Pre- and Post-Demonstration Levels of Ground-Water Parameters Indicative of Aquifer Quality

Ground-Water Parameter (applicable ground-water standard, if any) (mg/L)	Aquifer Depth	Pre-Demonstration (mg/L)[(a)]	Post-Demonstration[(b)] (mg/L)[(a)]
TCE (0.003)	Shallow	935 to 1,100	647 to 820
	Intermediate	960 to 1,070	60 to 174
	Deep	730 tot 892	3 to 920
cis-1,2-DCE (0.070)	Shallow	4 to 6	14 to 95
	Intermediate	5 to 26	9 to 80
	Deep	2 to 23	3 to 52
Vinyl chloride (0.001)	Shallow	<5	0.022 to <50
	Intermediate	<5	<0.010 to 1.7
	Deep	<5 to <83	0.032 to <50
pH	Shallow	6.9 to 7.1	6.3 to 7.6
	Intermediate	7.4 to 7.5	7.1 to 7.4
	Deep	7.2 to 7.5	6.5 to 6.8
ORP	Shallow	–130 to –108	–107 to –44
	Intermediate	–118 to –74	–89 to –68
	Deep	–142 to –106	–250 to –97
DO	Shallow	0.28 to 0.31	0.60 to 0.63
	Intermediate	0.27 to 0.40	0.99 to 1.11
	Deep	0.10 to 0.62	0.71 to 0.81
Calcium	Shallow	97 to 143	7 to 233
	Intermediate	60 to 70	14 to 153
	Deep	93 to 113	819 to 1,060
Magnesium	Shallow	23 to 37	<1 to 54
	Intermediate	54 to 74	1.2 to 77
	Deep	90 to 113	30 to 51
Alkalinity	Shallow	337 to 479	588 to 898
	Intermediate	351 to 465	243 to 434
	Deep	343 to 410	231 to 421
Chloride (250)	Shallow	37 to 38	141 to 383
	Intermediate	66 to 123	156 to 233
	Deep	11 to 774	3,520 to 4,800
Manganese (0.050)	Shallow	0.022 to 0.963	<0.015 to 0.079
	Intermediate	0.023 to 1.1	<0.015 to 0.11
	Deep	<0.015 to 0.02	0.021 to 0.16
Iron (0.3)	Shallow	0.78 to 3	<0.25 to 0.52
	Intermediate	0.33 to 11	<0.05 to 0.45
	Deep	<0.05 to 0.31	<0.25
Sodium	Shallow	17 to 24	113 to 467
	Intermediate	33 to 120	97 to 258
	Deep	325 to 369	1,530 to 3,130
TDS (500)	Shallow	548 to 587	1,330 to 1,750
	Intermediate	712 to 724	870 to 925
	Deep	1,030 to 1,980	7,220 to 10,600
BOD	Shallow	<3 to 20	32 to 42
	Intermediate	<3 to 9	3 to 4
	Deep	6 to 13	288 to 360
TOC	Shallow	6 to 6	35 to 45
	Intermediate	7 to 23	9 to 15
	Deep	9 to 40	270 to 300

(a) All reported quantities are in mg/L, except for pH (unitless), conductivity (mS/cm), and ORP (mV).

(b) Post-demonstration monitoring was conducted twice (December 2000 and June 2001) because some of the PA wells (PA-13 and PA-14) were plugged during the demonstration while their casings were being repaired. The cleaning process was performed after the initial post-demonstration monitoring in December 2000. Therefore, the results from the monitoring in June 2001 were incorporated in this table and the interpretation.

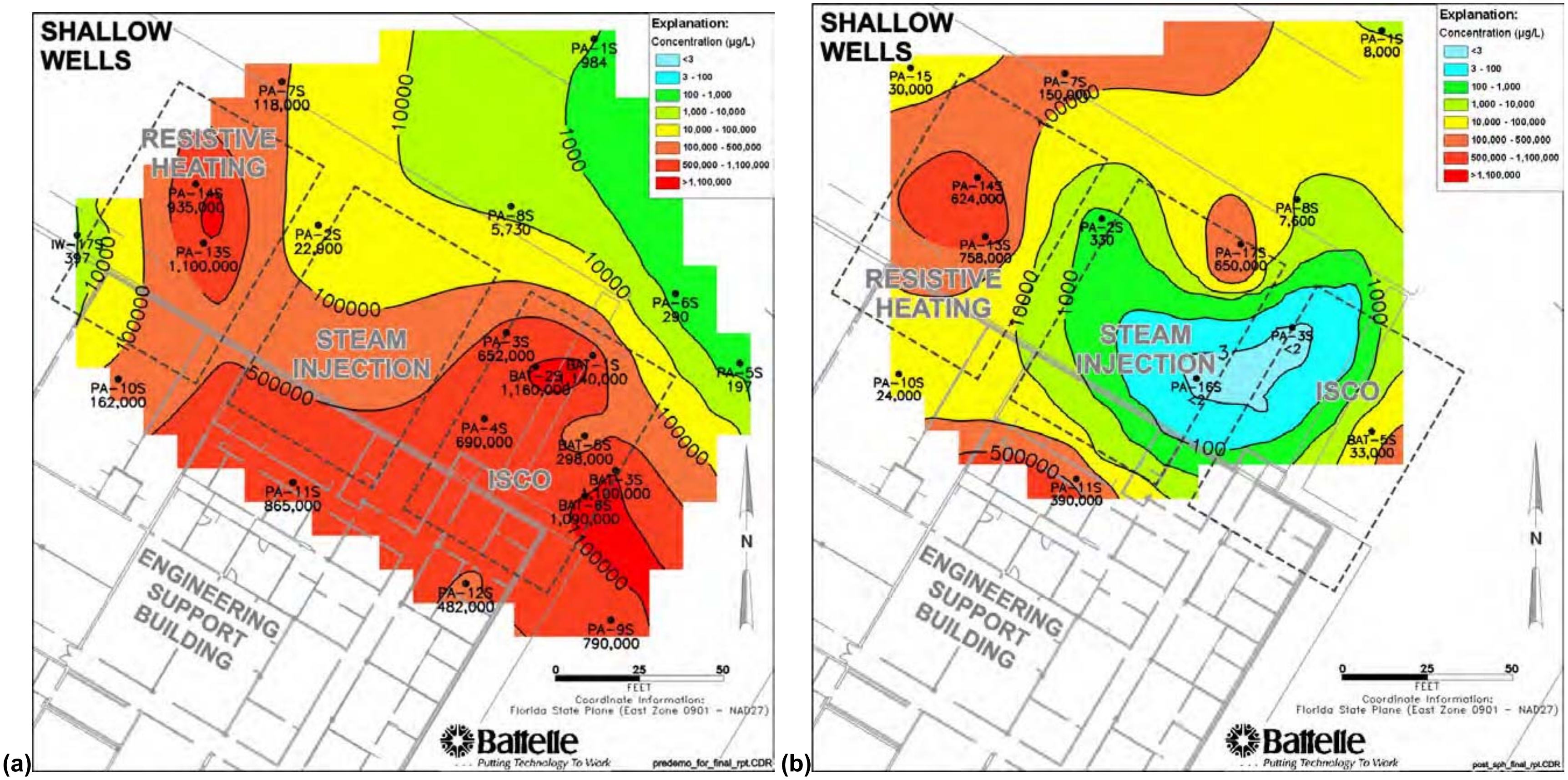


Figure 5-9. Dissolved TCE Concentrations (µg/L) during (a) Pre-Demonstration (August 1999) and (b) Post-Demonstration (December 2000) Sampling of Shallow Wells

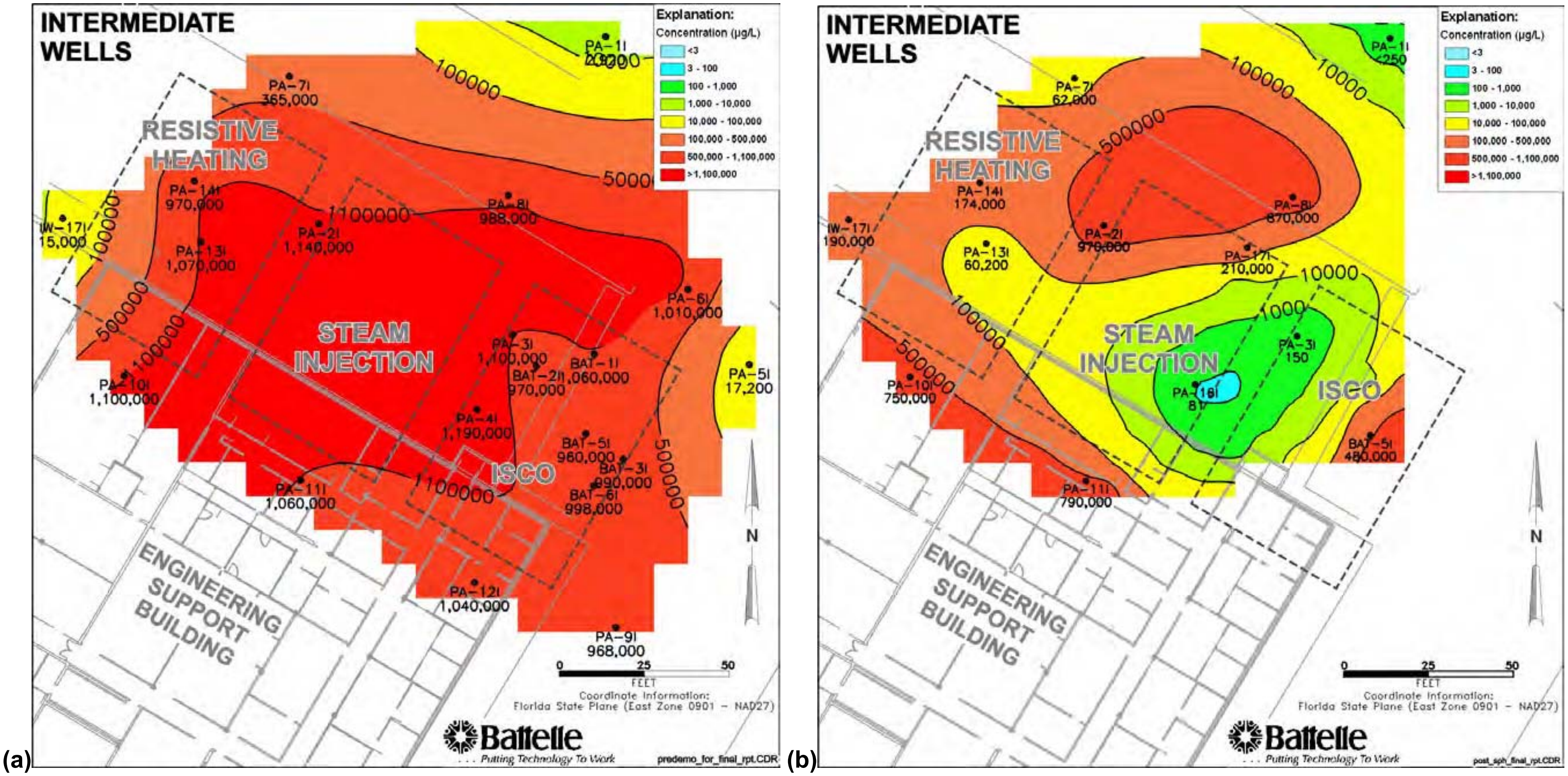


Figure 5-10. Dissolved TCE Concentrations (µg/L) during (a) Pre-Demonstration (August 1999) and (b) Post-Demonstration (December 2000) Sampling of Intermediate Wells

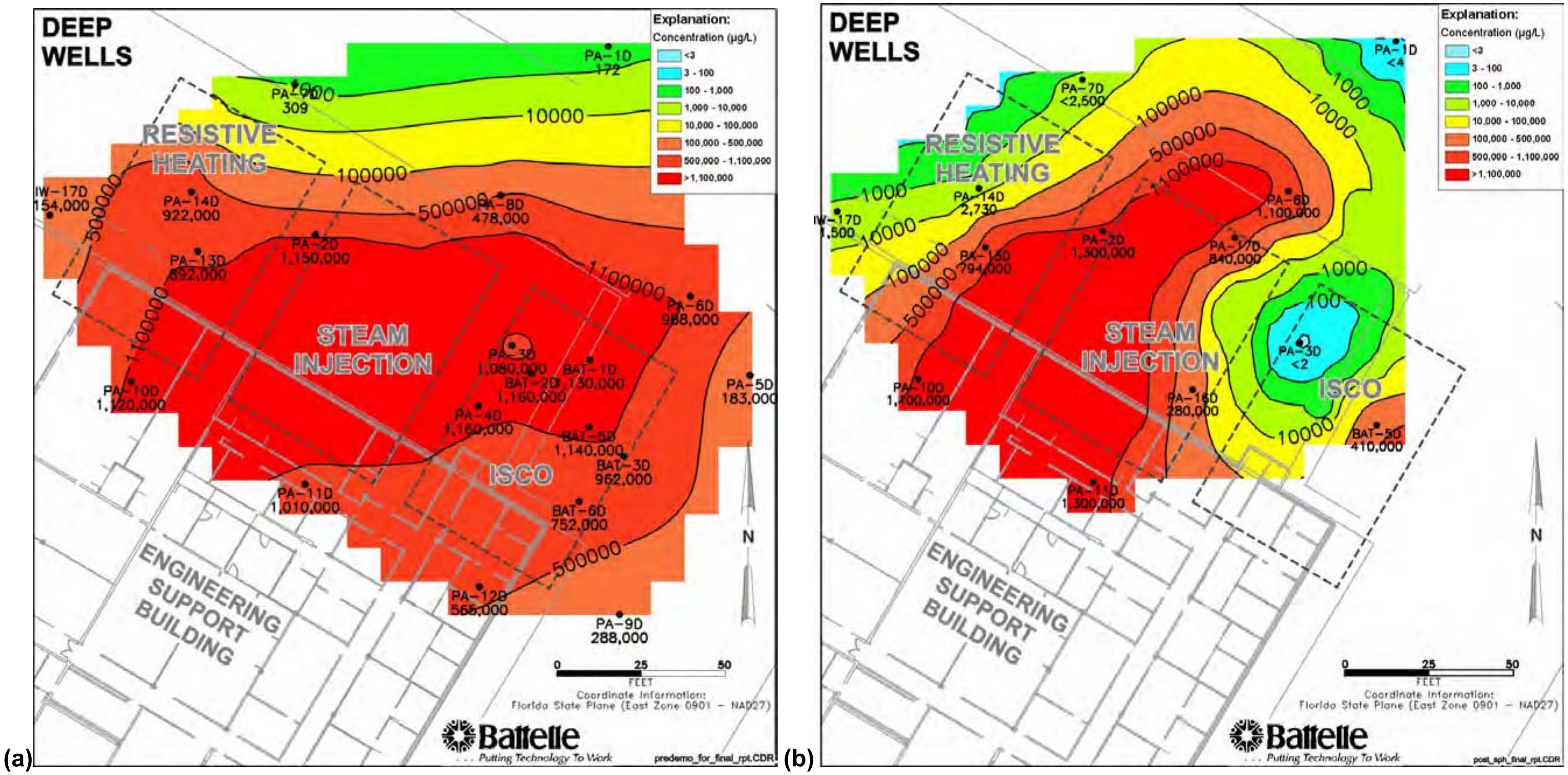


Figure 5-11. Dissolved TCE Concentrations (µg/L) during (a) Pre-Demonstration (August 1999) and (b) Post-Demonstration (December 2000) Sampling of Deep Wells

- Ground-water *pH* ranged from 6.9 to 7.5 before the demonstration to 6.3 to 7.6 after the demonstration, and relatively changed.
- *ORP* remained relatively unchanged, from −142 to −74 mV before the demonstration to −250 to −44 mV after the demonstration.
- *DO* ranged from 0.10 to 0.62 mg/L before the demonstration to 0.60 to 1.11 mg/L after the demonstration. Due to the limitations of measuring DO with a flowthrough cell, ground water with DO levels below 0.5 or even 1.0 is considered anaerobic. Except for the shallower regions, the aquifer was mostly anaerobic throughout the demonstration.
- *Specific Conductivity* increased from 0.776 to 3.384 mS/cm before the demonstration to 4.03 to 29.05 mS/cm after the demonstration. The increase is likely attributed to a buildup of dissolved ions due to the resistive heating treatment and also sea water intrusion.

Other ground-water measurements indicative of aquifer quality included inorganic ions, BOD, and TOC. The results of these measurements are as follows:

- *Calcium* levels increased sharply, from 60 to 143 mg/L before the demonstration to 7 to 1,060 mg/L after the demonstration. Magnesium levels remained relatively unchanged from before to after the demonstration. Ground-water *alkalinity* increased from 337 to 479 mg/L before the demonstration to 231 to 898 mg/L after the demonstration. The increases in calcium and alkalinity (carbonate) may be due to contributions from additional saltwater intrusion or from the effect of heat on the seashell material (aragonite [see Section 5.2.2.2]) in the soil matrix.
- *Chloride* levels may have been relatively high in the aquifer due to possible historical saltwater intrusion, especially in the deeper units. Despite relatively high native chloride levels in the aquifer, chloride concentrations increased sharply in the three stratigraphic units. In the shallow wells, chloride increased from 37 to 38 mg/L before the demonstration to 141 to 383 mg/L after the demonstration. In the intermediate wells, chloride increased from 66 to 123 mg/L before the demonstration to 156 to 233 mg/L after the demonstration. In the deep wells, chloride levels increased from 11 to 774 mg/L before the demonstration to 3,520 to 4,800 mg/L after the demonstration. These increased chloride levels normally would be a primary indicator of CVOC destruction. However, in this case, there are other possible sources of chloride (see Section 5.3.1). The secondary drinking water limit for chloride is 250 mg/L.
- *Manganese* levels in the plot decreased slightly from <0.015 to 1.1 mg/L before the demonstration to <0.015 to 0.16 mg/L after the demonstration; manganese has a secondary drinking water limit of 0.05 mg/L, which was exceeded during and after the demonstration. Perimeter wells also showed relatively unchanged levels of manganese (0.03 to 0.11 mg/L). Dissolved manganese consists of the species Mn^{7+} (from excess permanganate ion) and Mn^{2+} (generated when MnO_2 is reduced by native organic matter).
- *Iron* levels in the resistive heating plot remained relatively unchanged or decreased slightly, from <0.05 to 11 mg/L in the native ground water and <0.05 to 0.52 mg/L in the post-demonstration water; the secondary drinking water limit for iron is 0.3 mg/L, which was exceeded both before and after the demonstration. There was a possibility that chloride might corrode the stainless steel monitoring wells and dissolve some iron. This does not appear to have happened. In fact, it is possible that some dissolved iron precipitated out in the shallower regions of the aquifer.
- *Sodium* levels increased sharply, from 17 to 369 mg/L before the demonstration to 97 to 3,130 mg/L after the demonstration. Because sodium was not a concern as part of the resistive heating treatment, it was not measured during the demonstration.
- *Alkalinity* levels increased from 337 to 479 mg/L before the demonstration to 231 to 898 mg/L after the demonstration.
- Overall *sulfate* levels remained relatively constant, from 39 to 104 mg/L before the demonstration to 30 to 169 mg/L after the demonstration. However, sulfate levels did increase in the deep wells.
- *TDS* levels increased considerably in all three units. In the shallow wells, TDS levels rose from 548 to 587 mg/L before the demonstration to 1,330 to 1,750 mg/L after the demonstration; in the intermediate wells, TDS rose from 712 to 724 mg/L before to 870 to 925 mg/L after the demonstration; in the deep wells, TDS rose from 1,030 to 1,980 mg/L before to 7,220 to 10,600 mg/L after the demonstration. The secondary drinking water limit for TDS is 500 mg/L, which was exceeded both before and after the demonstration.
- *TOC and BOD* data were difficult to interpret. TOC in ground water increased from 6 to 40 mg/L before the demonstration to 9 to 300 mg/L after the

demonstration. BOD increased sharply in PA-13D and PA-14D, from <3 to 20 mg/L before the demonstration to 3 to 360 mg/L after the demonstration. The increase in ground-water TOC and BOD may indicate greater dissolution of native organic species (humic and fulvic materials) from the soil due to heating. TOC levels measured in soil increased sharply, ranging from <0.2 to 0.29 mg/kg before the demonstration to <100 to 986 mg/kg after the demonstration (see Table D-6 in Appendix D). The increase in soil TOC levels is difficult to explain; perhaps organic matter from surrounding regions deposited in the plot due to the heat-related convection.

Inorganic parameters were measured in the resistive heating plot wells, but they also were measured in the perimeter wells surrounding the plot and selected distant wells to see how far the influence of the applied technologies would progress. Further discussion about these inorganic parameters is presented in Section 5.3.1. The effect of the resistive heating treatment on the aquifer microbiology was evaluated in a separate study, as described in Appendix E.

5.2.2.2 Changes in Soil Geochemistry

In addition to the ground-water monitoring of geochemical parameters, post-demonstration soil samples were collected in the resistive heating plot and a control location in an unaffected area outside the plot (see Appendix D, Tables D-7 and D-8). These samples were initiated after unexpected drilling difficulties were encountered during post-demonstration soil coring by two different direct-push rigs at depths of approximately 16 to 18 ft bgs; neither rig could advance beyond this depth. Preliminary soil samples collected just above the obstruction depth were analyzed and appeared to indicate an increase in calcite deposits. An attempt was made later to penetrate the obstruction and collect additional soil samples for mineralogical analysis in order to evaluate any mineralogical changes that may have occurred due to the resistive heating application.

In May 2001, soil samples were successfully collected at multiple depths using a direct-push and vibratory hammer coring method. A visual inspection of the samples showed that they consisted of unconsolidated sand and contained whole shells and fragments of shell material (shell hash). Under low-power microscope the grains appeared coarse and ranged from light to dark in color, indicating the presence of several mineral types. No cementation of particles was observed.

Soil sample information is listed in Table 5-4. Cores labeled CCB1 were collected outside the resistive heating plot, and are thus expected to represent background

Table 5-4. Results of XRD Analysis (Weight Percent Abundances of Identified Minerals)

Core	Location	Depth (ft)	Quartz (%)	Calcite (%)	Aragonite (%)	Margarite (%)	Residue Error (%)
				Control			
CCB1	Outside the plot	16-18	85.0	5.3	7.6	2.1	69.0
CCB1		20-22	89.2	2.5	7.1	1.2	53.6
CCB1		22-24	95.7	0.5	3.5	0.2	68.4
CCB1		28-30	77.5	3.4	9.1	10.0	66.6
CCB1		32-34	54.1	5.5	37.8	2.6	65.2
CCB1		38-40	45.5	9.8	43.2	1.5	66.4
				Resistive Heating Plot			
CCB2	Inside the plot	16-18	86.8	2.0	9.9	1.3	70.5
CCB2		18-20	71.4	5.0	21.0	2.6	84.1
CCB2		22-24	88.8	1.7	7.1	2.5	67.6
CCB2[(a)]		28-30	NA	NA	NA	NA	NA
CCB2		30-33	70.8	6.5	20.6	2.2	56.4
CCB2		34-36	48.1	10.0	37.0	4.9	74.3
CCB3	Inside the plot	18-20	66.7	4.3	23.7	5.3	90.4
CCB3		20-22	66.0	2.3	5.9	25.9	72.6
CCB3		22-26	83.1	3.9	10.7	2.3	52.0
CCB3		26-30	67.8	6.0	24.3	1.9	57.8
CCB3		30-32	44.4	10.8	43.3	1.5	66.1
CCB3		38-40	46.6	11.4	38.0	4.0	89.2
CCB4	Inside the plot	16-18	52.6	11.5	33.8	2.1	84.7
CCB4		20-22	87.7	1.3	9.9	1.0	46.2
CCB4		24-26	64.8	5.2	27.3	2.7	77.3
CCB4		26-30	88.2	3.2	7.0	1.6	41.5
CCB4		34-36	69.5	3.4	23.3	3.8	94.0
CCB4		36-38	47.0	16.4	33.3	3.3	50.5

(a) In sample CCB2 (28-30 ft), a large unidentified peak occurred at 36.55° 2θ.

levels of minerals. Cores labeled CCB2, -3, and -4 were collected inside the SPH plot. The samples (24) were analyzed by x-ray diffraction (XRD) to determine relative abundances of minerals and other crystalline matter. XRD is a semiquantitative technique in which solid samples are analyzed nondestructively and without requiring preprocessing. Samples were scanned from 5° to 90° 2θ using a Rigaku powder diffractometer. Identification of compounds was facilitated by commercial software (Jade Software International) for matching observed peaks with known patterns from the Joint Commission on Powder Diffraction Files (JCPDF) database. Intensity measurements were converted to relative mass using relative Results of the XRD analysis are given in Table 5-4. Note that the composition of sample CCB2 (28-30 ft) was not determined due to the presence of a large unidentified peak, which would have rendered such a calculation uncertain.

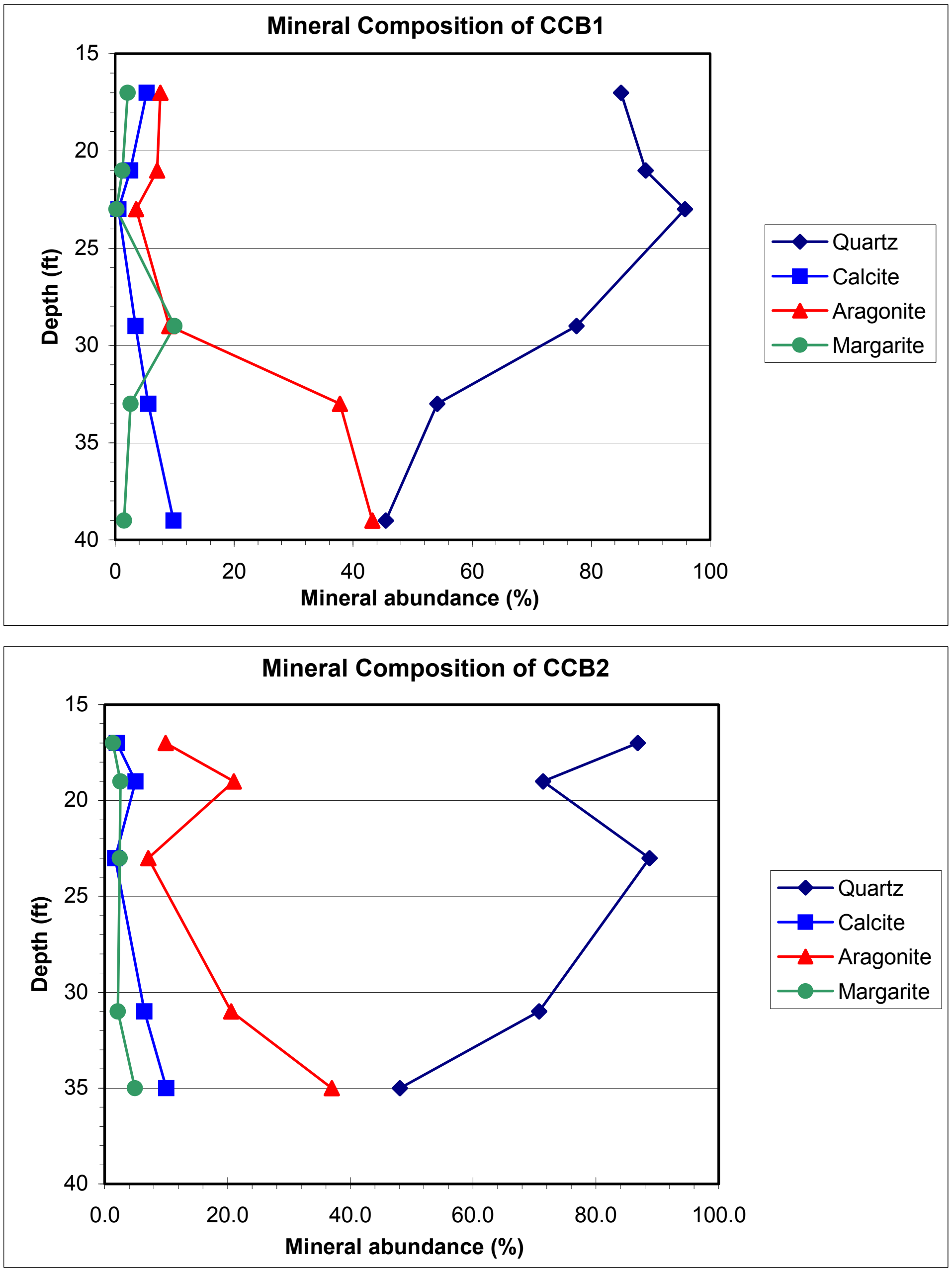
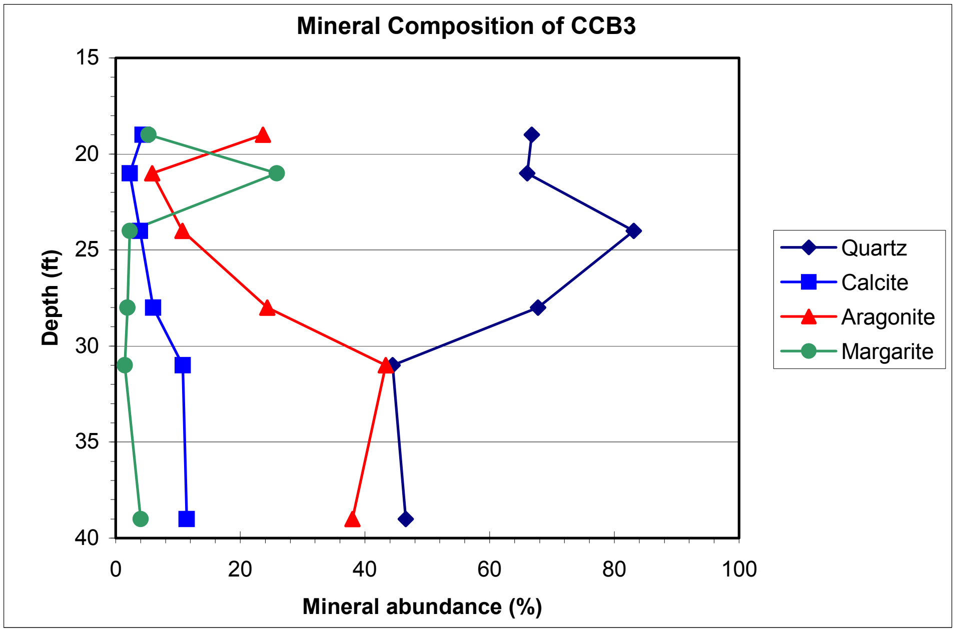


Figure 5-12. Mineral Abundance in Control (CCB1) and Resistive Heating Plot (CCB2) Soil Samples



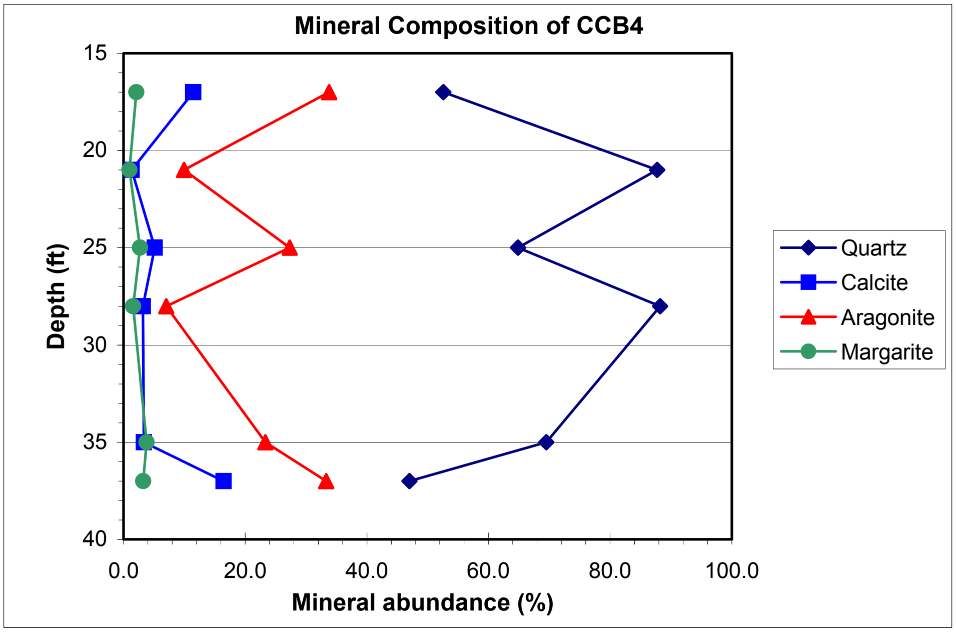


Figure 5-13. Mineral Abundance in Resistive Heating Plot Soil Samples CCB3 and CCB4

Graphs based on the data in Table 5-4 help illustrate the distribution of minerals in the subsurface in Figures 5-12 and 5-13. These data show that quartz and aragonite make up the majority of minerals identified in the core samples. The maximum amount of aragonite seems to occur at 30 to 40 ft bgs. Aragonite may be associated with shell material; if this is the case, then the increase in aragonite at 30 to 40 ft could coincide with a native sediment layer that is high in shell material. Calcite and margarite (mica) are less abundant. There appears to be a tendency for calcite to increase slightly with depth, which also corresponds to the ground-water monitoring of calcium.

In summary, the mineralogical composition of the post-demonstration resistive heating plot soil does not appear to be noticeably different from that of the soil in the unaffected region (control). It is possible that the drilling problem was a transient phenomenon or that it was caused by a change in the texture of the soil rather than by its composition.

5.2.3 Changes in the Hydraulic Properties of the Aquifer

Table 5-5 shows the results of pre- and post-demonstration slug tests conducted in the resistive heating plot wells. The hydraulic conductivity of the aquifer remained relatively unchanged during the resistive heating application.

Table 5-5. Pre- and Post-Demonstration Hydraulic Conductivity in the Resistive Heating Plot Aquifer

	Hydraulic Conductivity (ft/day)	
Well	Pre-Demonstration	Post-Demonstration
PA-13S	14.1	17.4
PA-13I	2.4	1.2
PA-13D	1.1	5.4
PA-14S	10.3	23.6
PA-14I	4.1	11.4
PA-14D	1.9	7.3

5.2.4 Changes in the Microbiology of the Resistive Heating Plot

Microbiological analysis of soil and ground-water samples was conducted to evaluate the effect of resistive heating treatment on the microbial community (see Appendix E.3 for details). Samples were collected before and twice (eight months and eighteen months) after the resistive heating demonstration. During pre- and post-demonstration monitoring events, soil samples were collected from five locations in the plot and five locations in a control (unaffected) area. Eighteen (18) months after the demonstration was complete, only three sets of samples were collected at similar depths in the plot. The results are presented in Appendix E.3.

Table 5-6 summarizes the soil analysis results. The geometric mean typically is the mean of the five samples collected in each stratigraphic unit in the plot. The eight months of time that elapsed since the end of resistive heating application and collection of the microbial samples may have given time for microbial populations to reestablish. Only in the Middle Fine-Grained Unit does it seem that the resistive heating application caused a reduction in microbial populations that persisted until the sampling. If microbial populations were reduced immediately after the demonstration, they seem to have reestablished in the following eight months. In the capillary fringe and in the Upper Sand Unit, microbial populations appeared to have increased by an order of magnitude. The persistence of these microorganisms despite the autoclave-like conditions in the resistive heating plot may have positive implications for biodegradation of any TCE residuals following the resistive heating treatment.

5.2.5 Summary of Changes in Aquifer Quality

Application of the resistive heating technology caused the following changes in the treated aquifer:

- Dissolved TCE levels declined in several monitoring wells in the resistive heating plot, although none of the wells showed post-demonstration concentrations of less than 5 µg/L, the federal drinking water standard, or 3 µg/L, the State of Florida ground-water target cleanup level. *Cis*-1,2-DCE levels remained above 70 µg/L and increased considerably in some wells. Vinyl chloride (1 µg/L State of Florida target) levels could not be accurately determined because higher TCE and *cis*-1,2-DCE levels elevated the detection limits of vinyl chloride. This indicates that, in the *short term*, removal of DNAPL mass from the targeted aquifer caused ground-water TCE concentrations to decline. Dissolved-phase

Table 5-6. Geometric Mean of Microbial Counts in the Resistive Heating Plot (Full Range of Replicate Sample Analyses Given in Parentheses)

Resistive Heating Plot	Pre-Demonstration Aerobic Plate Counts (CFU/g)	Post-Demonstration Aerobic Plate Counts (8 months after) (CFU/g)	Pre-Demonstration Anaerobic Viable Counts (Cells/g)	Post-Demonstration Anaerobic Viable Counts (8 months after) (Cells/g)
Capillary Fringe	32,680 (12,589 to199,526)	3,285,993 (63,096 to 63,095,734)	32,680 (3,162 to 1,584,893)	2,818,383 (79,433 to 15,848,932)
Upper Sand Unit	575 (<316 to 6,310)	5,410 (100 to 1,258,925)	1,050 (158 to 50,119)	11,961 (126 to 15,848,932)
Middle Fine-Grained Unit	2,370 (200 to 1,584,893)	<316.2(a)	10,000 (501 to 1,258,925)	251.2(a)
Lower Sand Unit	856 (<316 to 25,119)	758 (158 to 25,119)	1,711 (251 to 63,096)	2,188 (251 to 50,119)

(a) Only one sample was collected in this stratigraphic unit.

CVOCs were not as efficiently removed, especially from the upper portions of the aquifer, probably due to the lower heating/stripping efficiency in the shallower regions.

- Compared to short-term post-demonstration levels, dissolved TCE levels in the plot in the *intermediate term* could either increase (due to rebound from any remaining DNAPL) or decrease (due to continued degradation of CVOCs by any abiotic or biological mechanisms). Because resistive heating treatment has depleted the DNAPL source, any intermediate term rebound in TCE concentrations is not likely to restore dissolved TCE levels to pre-demonstration levels. A weakened plume may be generated and the resulting CVOC levels may be more amenable to natural attenuation. The downgradient point at which ground water meets federal or state cleanup targets is likely to move closer to the DNAPL source, resulting in a concomitant risk reduction.
- In the *long term*, DNAPL mass removal is expected to lead to eventual and earlier depletion of the plume and earlier dismantling of any interim remedy to control plume movement.
- The TCE degradation product *cis*-1,2-DCE, which also is subject to drinking water standards (70 µg/L), appeared to be accumulating in the ground water in the test plot, and its buildup could be a concern. Its accumulation may indicate that the degradation rate of *cis*-1,2-DCE is not as fast as the degradation rate of TCE, under the conditions prevalent in the aquifer.
- Ground-water pH and dissolved oxygen levels remained relatively constant, but chloride, sodium, potassium, sulfate, alkalinity (carbonate), and TDS levels rose sharply. TDS levels were above the secondary drinking water standard of 500 mg/L both before and after the demonstration, classifying the aquifer as brackish. Sources of these dissolved solids could include evaporative residue, saltwater intrusion, displacement of exchangeable sodium from aquifer minerals, and/or CVOC degradation.
- Biological oxidation demand and TOC levels in the ground water generally increased. These increases could be due to dissolution of humic and fulvic matter in the aquifer under the heat treatment.
- The ground-water levels of iron, chromium, and nickel remained relatively constant. There does not appear to be any significant corrosion of the stainless steel monitoring wells of the kind experienced in the ISCO plot.
- Slug tests conducted in the resistive heating plot before and after the demonstration did not indicate any noticeable changes in the hydraulic conductivity of the aquifer.
- Although difficulties were encountered in operating the drill rig during post-demonstration coring, the geochemical composition of the soil does not appear to have changed much due to the heat treatment. Quartz and aragonite make up the majority of the minerals identified in soil samples from heat-affected and unaffected regions of the aquifer. Aragonite may be associated with the seashell fragments found in fair abundance in the aquifer. Calcite and margarite (mica) are less abundant in the aquifer.

5.3 Fate of the TCE-DNAPL Mass in the Plot

This part of the assessment was the most difficult because the DNAPL could have taken one or more of the following pathways when subjected to the resistive heating treatment:

- TCE recovery in the resistive heating vapor recovery system
- TCE-DNAPL degradation through biological or abiotic mechanisms
- DNAPL migration to surrounding regions
- Potential TCE losses during post-demonstration sampling of hot soil cores.

Vapor sampling conducted by the resistive heating vendor indicates that 1,947 kg of total TCE was recovered in the vapor extraction system. The initial estimate of total TCE mass in the subsurface was 11,313 kg. Other pathways that the TCE in the plot may have taken are discussed in this section.

The chloride mass estimates, which are potential TCE degradation indicators, are considered somewhat coarse approximations for the following reasons:

- *Relatively low sampling density* compared to the sampling density for TCE, which was the main focus of the performance assessment
- *Possible migration of chloride in directions where there are no monitoring wells* (e.g., east and southeast side of ISCO plot and west and southwest side of resistive heating plot). The samples labeled CHL-# and collected with a Geoprobe® by FSU and NASA do help to cover some of these data gaps.
- *Timing of post-demonstration samples*. Because the ISCO and resistive heating demonstrations

ended at different times, the post-demonstration sampling for the two plots and perimeter wells was spread over several months. In the absence of an artificial gradient (such as that created in the ISCO plot during injection in April 2000), the ground water is relatively stagnant; therefore, any changes in chloride levels during the somewhat wide sampling period are likely to be due to diffusion and therefore relatively low.

Despite these limitations, a chloride evaluation does provide some insights into the occurrences in the two test plots.

5.3.1 TCE-DNAPL Degradation through Biological or Abiotic Mechanisms

As reported in Appendix D, ground-water samples collected from the Launch Complex 34 wells and GeoProbe® monitoring points were analyzed for chloride (see Figure 5-14 for sampling locations). The chloride analysis was evaluated because an increase in chloride levels is a potential indicator of CVOC degradation, either by abiotic or biologically mediated pathways. Table 5-7 shows the changes in concentrations of chloride and other ground-water constituents in the resistive heating plot. Figures 5-15 to 5-17 show the distribution of excess chloride concentrations in the ground water at Launch Complex 34—excess chloride plotted in these figures is the difference in chloride concentrations between post-demonstration and pre-demonstration (baseline) levels. The excess chloride represents chloride accumulating in the aquifer at Launch Complex 34 due to the implementation of the resistive heating and/or ISCO technologies. Chloride levels rose in both resistive heating and ISCO plots by 7 to 10 times the pre-demonstration concentration in the resistive heating plot wells.

As shown in Table 5-8, the chloride concentrations were converted to chloride masses in different target regions of the aquifer. The mass estimates in Table 5-8 were done using four target boundaries:

- Each individual test plot only
- Each test plot and its perimeter (extending up to the nearest perimeter well outside the plot). This was done on the assumption that the chloride generated inside the plot spreads at least to the immediate perimeter area around the plot.
- Each test plot and its perimeter, as well as the areas covered by the GeoProbe® samples (labeled "CHL" samples) collected by FSU, following the resistive heating and ISCO demonstrations. The GeoProbe® samples provide additional resolution to the perimeter areas.
- All three plots ("entire site") and their perimeter (with and without the CHL sample data).

The interpolation used to calculate the masses in Table 5-8 is linear and the contouring software (EarthVision™) used for estimating TCE mass was also used to estimate chloride mass. The volumetric package in this application software calculates the volume of isoconcentration shells that are contoured in three dimensions using the spatial chloride data. A chloride mass is calculated in each isoconcentration shell covering the region of interest (e.g., test plot only, or test plot and perimeter, etc.). For both plots, the total increase in chloride mass is much larger when the chloride levels in the perimeter wells are taken into account. This shows that the chloride formed in the plot spreads to surrounding regions.

At Launch Complex 34, there are a variety of factors that make it important that the chloride data not be viewed in isolation. Rather, due to the particular site characteristics of Launch Complex 34, the changes in chloride need to be viewed from the perspective of site location, aquifer geochemistry, the type of treatments applied in the test plots, and any crossover effects due to the simultaneous implementation of the resistive heating and ISCO technologies. TDS levels rose in several monitoring wells following the demonstration at Launch Complex 34, and only a part of this increase is attributable to chloride. Therefore, it also is important to identify potential sources for the increased levels of dissolved constituents other than chloride.

The elevated chloride concentrations (and masses) in the resistive heating plot can be attributed to one or more of the following causes:

- Evaporation of ground water from the resistive heating plot
- Redistribution of ground water due to convection, advection and displacement
- Dechlorination of TCE, *cis*-1,2-DCE, and/or vinyl chloride due to microbial interaction
- Saltwater intrusion into the resistive heating plot
- Migration from the ISCO plot
- Dechlorination of TCE, *cis*-1,2-DCE, and/or vinyl chloride by abiotic mechanisms.

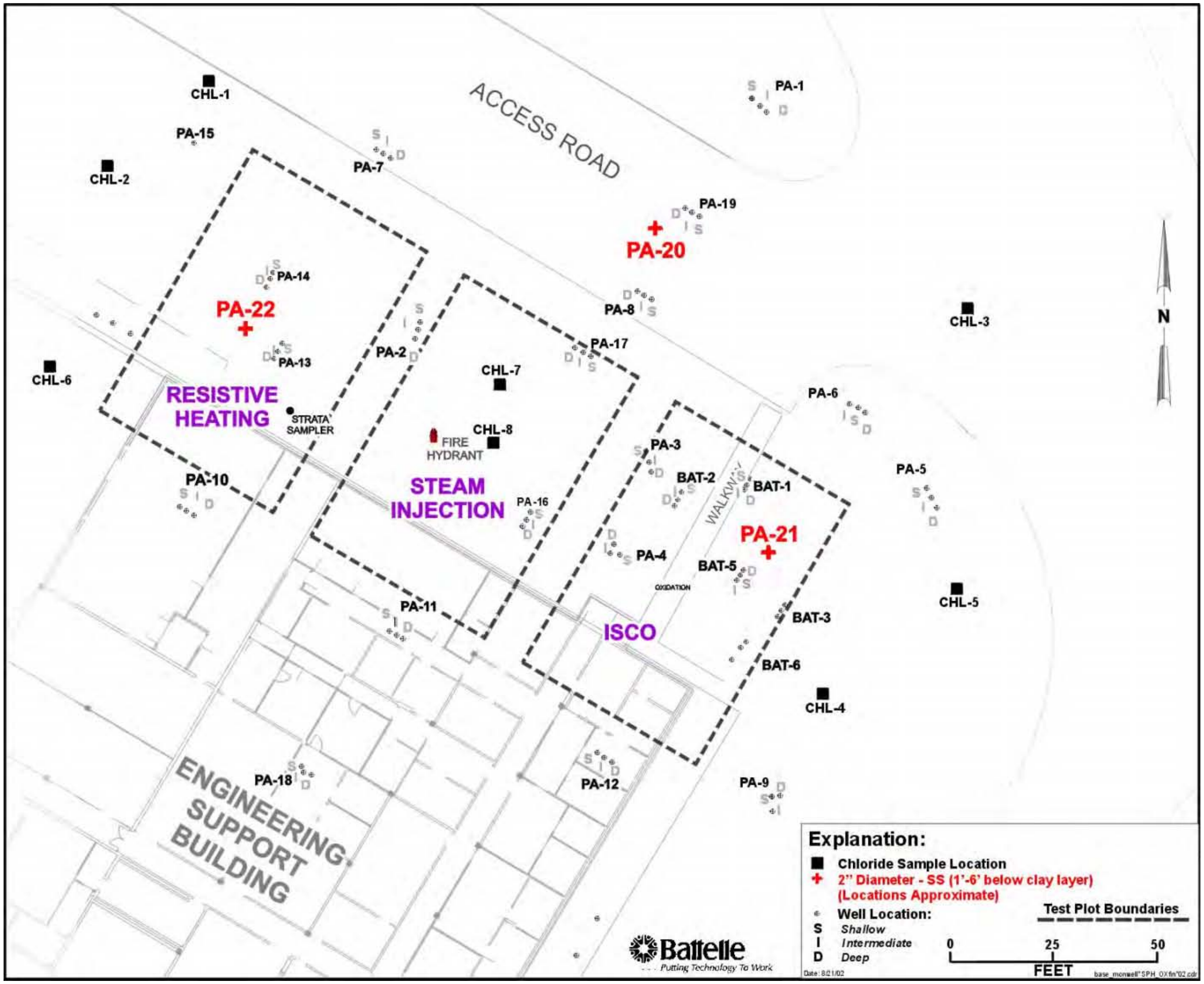


Figure 5-14. Monitoring Wells and GeoProbe® Monitoring Points (CHL-#) for Chloride Analysis (Sampled January to May 2001)

Table 5-7. Pre- and Post-Demonstration Inorganic and TOC/BOD Measurements in Resistive Heating Plot Wells

	Calcium			Magnesium			Sodium			Potassium		
Well ID	Pre-Demo	Post-Demo	July 2001	Pre-Demo	Post-Demo	July 2001	Pre-Demo	Post-Demo	July 2001	Pre-Demo	Post-Demo	July 2001
PA-13S	<1	**233**	**97.4**	23.4	54.4	40	23.9	**161**	**113**	< 5	**126**	**174**
PA-13I	70.1	NA	153	54	NA	76.5	33.1	NA	96.7	13	NA	49
PA-13D	113	**819**	**647**	113	51.4	75	369	**2,070**	**1,530**	20	**136**	86
PA-14S	97.4	6.6	55.3	37.4	<1	10.6	17.4	**467**	**138**	NA	9.8	43
PA-14I	60.3	NA	13.6	73.7	NA	1.2	120	NA	258	NA	NA	14
PA-14D	93.1	**1,060**	**662**	90.3	30	30.2	325	**3,130**	**2,490**	NA	143	94

	Chloride			NO_3-NO_2			Sulfate			Alkalinity as $CaCO_3$		
Well ID	Pre- Demo	Post-Demo	July 2001	Pre- Demo	Post-Demo	July 2001	Pre-Demo	Post-Demo	July 2001	Pre-Demo	Post-Demo	July 2001
PA-13S	38	**383**	277	<0.1	<0.1	<0.1	74	169	123	479	588	424
PA-13I	66	NA	233	<0.1	NA	<0.1	64.8	NA	150	351	NA	243
PA-13D	NA	**4800**	**3610**	<0.1	<0.1	0.21	78.3	166	139	410	231	268
PA-14S	37	141	101	<0.1	<0.1	<0.1	39	37.1	18.6	337	898	388
PA-14I	123	NA	156	<0.1	NA	<0.1	104	NA	30	465	NA	434
PA-14D	774	**3520**	**4790**	<0.1	<0.1	<0.1	68.3	117	163	343	421	394

	TDS (mg/L)			BOD (mg/L)			TOC (mg/L)		
Well ID	Pre- Demo	Post-Demo	July 2001	Pre-Demo	Post-Demo	July 2001	Pre-Demo	Post-Demo	July 2001
PA-13S	583	**1,750**	**1,190**	20	32.4	25.8	5.6	**44.8**	**39.6**
PA-13I	NA	NA	925	<3	NA	3.3	7.1	NA	14.9
PA-13D	NA	**10,600**	**8,360**	13.2	**360**	**360**	39.6	**300**	**273**
PA-14S	548	**1,330**	772	<3	**42**	**22.2**	5.7	34.7	18.7
PA-14I	724	NA	870	8.9	NA	3.7	23.4	NA	8.9
PA-14D	1,980	**7,220**	**10,700**	6	**288**	**560**	9	**270**	**326**

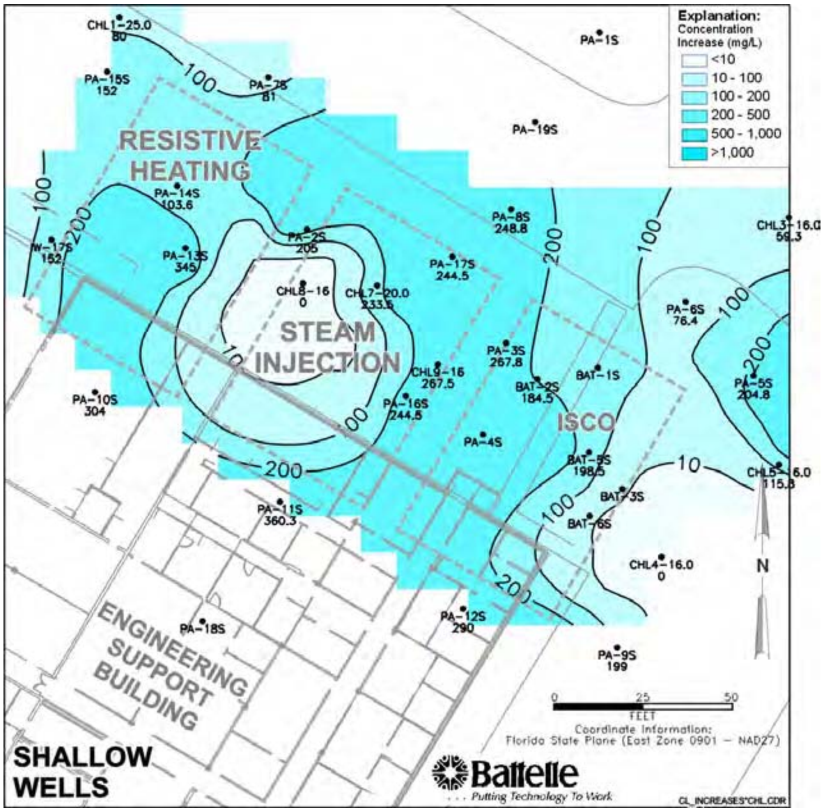


Figure 5-15. Increase in Chloride Levels in Shallow Wells (Sampled January to May 2001)

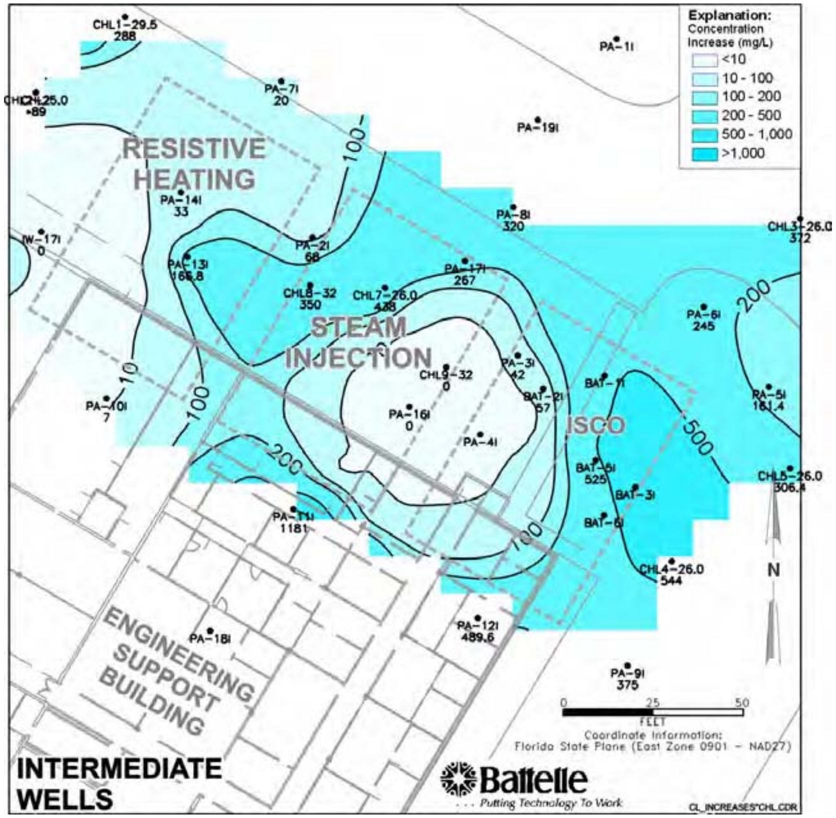


Figure 5-16. Increase in Chloride Levels in Intermediate Wells (Sampled January to May 2001)

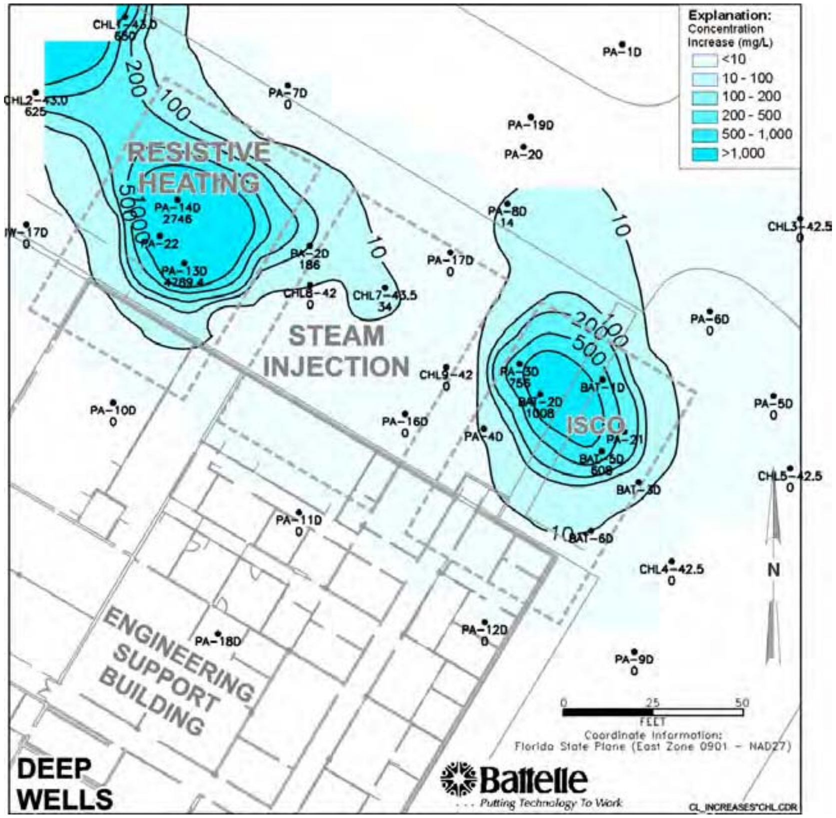


Figure 5-17. Increase in Chloride Levels in Deep Wells (Sampled January to May 2001)

Table 5-8. Chloride Mass Estimate for Various Regions of the Launch Complex 34 Aquifer

Boundaries for Estimate	Pre-Demonstration Chloride Mass (kg)	Post-Demonstration Chloride Mass (kg)	Increase in Chloride Mass (kg)	% Increase in Mass (%)
ISCO Plot Only	828	1,822	994	120%
Resistive Heating Plot Only	524	2,160	1,636	**312%**
ISCO Plot and Perimeter	2,438	4,934	2,495	102%
Resistive Heating Plot and Perimeter	1,606	4,241	2,635	**164%**
ISCO Plot and Perimeter/CHL Data	3,219	5,524	2,304	72%
Resistive Heating Plot and Perimeter/CHL Data	1,722	4,491	2,770	**161%**
Entire Site	4,264	9,188	4,923	115%
Entire Site with CHL Data	4,900	9,118	4,219	86%

Boldface in the table denotes the significant increase of chloride mass after the application of the resistive heating treatment.

5.3.1.1 Evaporation as a Potential Source of Chloride

The thermal treatment in the resistive heating plot causes some ground water to evaporate, leaving behind dissolved solids (including chloride) as residue. Table 5-9 provides a calculation of the amount of chloride that may have been deposited in the resistive heating plot by the water evaporating due to the heating. The 371,074 L of condensate collected above ground would have left behind 153 kg of chloride, if only the measurements in the wells inside the plot are taken into account (that is, the concentrations in PA-13 and PA-14 are assumed to extend to the boundaries of the plot). If the measurements in the perimeter wells are taken into account, 468 kg of chloride would have been left behind by the condensate. The chloride deposited by evaporation accounts for only 9 to 18% of the total increase in chloride in the resistive heating plot.

5.3.1.2 Microbial Degradation as a Source of Chloride

It is possible that some TCE was reductively dechlorinated due to microbial interactions. The biological sampling (see Section 5.2.4) indicated that microbes did survive after the heat treatment. Considerably elevated levels of *cis*-1,2-DCE, a degradation byproduct, are also apparent in some monitoring wells in and around the resistive heating plot (see the *cis*-1,2-DCE analysis summary in Table 5-10), although in one of the wells (PA-14D), *cis*-1,2-DCE levels dropped sharply following the demonstration. If microbial degradation is a viable mechanism, one concern would be the buildup of *cis*-1,2-DCE, which is subject to applicable ground-water cleanup standards (typically 70 µg/L). Degradation of TCE by reductive dechlorination may be a much faster process as compared to degradation of *cis*-1,2-DCE under the anaerobic conditions of the aquifer. Persistence of *cis*-1,2-DCE

Table 5-9. Contribution of Chloride from Evaporation in the Resistive Heating Plot and Vicinity

Calculated Parameter	Chloride Mass Estimation Using Resistive Heating Plot Well Data Only[(a)]	Chloride Mass Estimation Using Resistive Heating Plot and Perimeter Well Data
Pre-Demonstration Chloride Mass	524 kg	1,606 kg
Volume of Water Condensate Recovered	371,074 L (98,038 gal)	371,074 L (98,038 gal)
Volume of Pore Water in Plot (based on a porosity of 0.3)	1,274,265 L	1,274,265 L
Estimated Chloride Mass Left Behind by Condensate	153 kg	468 kg
Estimated Total Increase in Chloride Mass in the Plot (from Table 5-1)	1,636 kg	2,635 kg
Amount of Total Increase in Chloride Mass Accounted for by Evaporative Residue	9%	18%

(a) Based on chloride concentrations in monitoring well clusters PA-13 and PA-14.

Table 5-10. *cis*-1,2-DCE Levels in Resistive Heating Plot and Perimeter Wells

Well ID	Pre-Demo	Post-Demo	June 2001
Resistive Heating Plot Wells			
PA-13S	4,400	21,000 J	14,000
PA-13I	4,900	NA	9,370
PA-13D	2,200	18,000 J	52,000
PA-14S	5,880	95,000	73,800
PA-14I	26,000	NA	80,000
PA-14D	21,900	1,100	2,660
Resistive Heating Plot Perimeter Wells			
PA-2S	3,020	6,000	NA
PA-2I	5,480	11,000 J	NA
PA-2D	2,700	<33,000	NA
PA-7S	22,100	130,000	NA
PA-7I	160,000	170,000	NA
PA-7D	21	30,000	NA
PA-10S	8,880	19,000	NA
PA-10I	4,700J	12,000 J	NA
PA-10D	2,400J	23,000 J	NA
IW-17S	593	Dry	NA
IW-17I	123,000	30,000	NA
IW-17D	39,200	16,000 D	NA
PA-15	NA	170,000	NA

and probably vinyl chloride (which was not detected in many ground-water samples due to the masking effect of TCE and *cis*-1,2-DCE) in the aquifer is a concern. The limiting conditions obstructing *cis*-1,2-DCE degradation may need to be determined and addressed to control *cis*-1,2-DCE and vinyl chloride plume strengthening.

5.3.1.3 Saltwater Intrusion as a Source of Chloride

It is *possible* that saltwater intrusion into the resistive heating plot led to the sharp increases in sodium and chloride. No other source is apparent that would contribute to such high levels of both sodium and chloride, which are the two main constituents of seawater (see Table 5-11). Sodium increased by up to 9 times in the resistive heating plot wells, an increase similar in proportion to the increase in chloride. Both sodium and chloride are especially high in the deeper regions of the aquifer. Heating of the plot and the resulting convection could cause the highly saline water at the bottom of the aquifer to rise into the bulk of the aquifer. This water would then be replaced with additional saline water from the bottom of the surrounding aquifer regions. The elevated temperatures in the resistive heating plot could have caused an increase in the solubility of sodium and chloride and contributed to the retention of chloride in the plot. Because of normally stagnant ground-water conditions in the plot, the sodium and chloride could be retained in the plot during the subsequent cooling of the ground water. The noticeable increases in sulfate, potassium, and calcium levels in the plot also are indicative of saltwater intrusion, although, unlike sodium, they could have come from other sources— the calcium from the seashell material in the aquifer, and/or the calcium, potassium, and sulfate from migration from the ISCO plot.

Table 5-11. Seawater Composition

Element	Concentration (mg/L)
Chloride	18,980
Sodium	10,561
Magnesium	1,272
Sulfur	884
Calcium	400
Potassium	380

It is possible that some *exchangeable* sodium was released from clay minerals when the Middle Fine-Grained Unit or Lower Clay Unit (aquitard) was heated. Alternatively, some influx of potassium ion from the ISCO plot (see Section 5.3.2.1) could have caused displacement of sodium ions. But the relatively low proportion of the clay (approximately 1.5 ft thick) versus the sandy/silty aquifer (40 ft thick) makes it unlikely that so much sodium was contributed to the aquifer by the clay.

5.3.1.4 Migration from the ISCO Plot as a Source of Chloride

It is possible that some chloride migrated from the ISCO plot, just as the potassium did. Increased levels of these constituents in the wells between the oxidation and resistive heating plots are indicative of this pathway. As seen in Tables 5-12 and 5-13 and in Figures 5-15 to 5-17, many of the monitoring wells in the migration path, such as PA-16, PA-17, PA-8, and PA-11 in the steam plot and vicinity, showed increased levels of chloride and TDS, especially in the shallow and intermediate levels. The increase in potassium can be similarly tracked from the ISCO plot to the resistive heating plot, as reported in the Fourth Interim Report (Battelle, 2000b). Similar migration trends can be seen for calcium, alkalinity, TOC, and BOD, which increased in the steam injection plot wells as well. Part of the increase in potassium levels in the resistive heating plot could have been due to saltwater intrusion rather than crossover from the ISCO plot.

5.3.1.5 Abiotic Degradation as a Source of Chloride

It is possible that some TCE was degraded abiotically by reductive dechlorination caused by exposure of the ground water and TCE to the carbon steel shot used in the electrodes. The steel shot are relatively fine and not too different in size and composition from the granular cast iron used in permeable barriers for ground-water treatment. Other possible abiotic mechanisms are heat-induced hydrolysis or oxidation.

Table 5-12. Chloride and TDS Measurements in Monitoring Wells Surrounding the Resistive Heating Plot

	Chloride (mg/L)			TDS (mg/L)	
Well ID	Pre-Demo	ISCO Post-Demo	Resistive Heating Post-Demo	Pre-Demo	Post-Demo
Resistive Heating Perimeter Wells					
PA-2S	34[(a)]	247	243	520[(a)]	915
PA-2I	55[(a)]	234	191	580[(a)]	1,050
PA-2D	760[(a)]	695	960	1,700[(a)]	2,720
PA-7S	NA	NA	119	NA	657
PA-7I	NA	NA	143	NA	752
PA-7D	NA	NA	531	NA	1,260
PA-7D-DUP	NA	NA	522	NA	1,270
PA-10S	NA	NA	342	NA	1,040
PA-10I	NA	NA	130	NA	789
PA-10I-DUP	NA	NA	128	NA	777
PA-10D	NA	NA	701	NA	1,580
IW-17S	NA	NA	NA	NA	NA
IW-17I	NA	NA	73.7	NA	663
IW-17D	NA	NA	640	NA	1,350
PA-15	NA	NA	190	NA	975
Resistive Heating Vicinity Wells					
PA-16S	NA	NA	<1,000	NA	2,470
PA-16I	NA	NA	42.8	NA	814
PA-16D	NA	NA	415	NA	4,510
PA-17S	NA	NA	297	NA	1,740
PA-17I	NA	NA	448	NA	1,360
PA-17D	NA	NA	305	NA	1,200
PA-17D-Dup	NA	NA	318	NA	1,340
PA-8S	24.2	273	101	445	1,600
PA-8S-DUP	NA	NA	NA	NA	NA
PA-8I	119	439	504	706	2,200
PA-8D	774	788	640	1,410	1,910
PA-8D-DUP	NA	NA	NA	NA	NA
PA-11S	36.7	397	357	531	2,900
PA-11I	49	1,230	635	549	3,790
PA-11D	819	756	737	1,540	1,670
PA-11D-DUP	NA	NA	NA	NA	NA

(a) Pre-demonstration levels of chloride in PA-2 are based on concentrations in neighboring wells. PA-2 itself was not one of the wells sampled for chloride during the pre-demonstration event.

Table 5-13. Inorganic and TOC Measurements (mg/L) in Ground Water from the Steam Injection Plot after Resistive Heating Demonstration[(a)]

Well ID	Sodium	Potassium	Calcium	Magnesium	Sulfate	Alkalinity	TOC
PA-16S	45	1,560	28	<2	<1,000	661	1,680
PA-16I	42	511	31	4	104	380	31
PA-16D	72	1,600	111	179	681	2,500	134
PA-17S	189	330	108	74	293	1,430	74
PA-17I	213	33	93	101	120	422	2
PA-17D	147	103	91	100	202	479	20

(a) These wells were installed only after the resistive heating and ISCO treatment demonstrations were completed. The parameter levels before the resistive heating and ISCO treatments began (see Table 5-3) can be compared to the values in the surrounding wells.

5.3.2 Potential for DNAPL Migration from the Resistive Heating Plot

The seven measurements conducted to evaluate the potential for DNAPL migration to the surrounding aquifer include:

- Hydraulic gradient in the aquifer
- Temperature measurements in the resistive heating plot and vicinity
- Distribution of dissolved potassium in the aquifer
- TCE measurements in perimeter wells
- TCE concentrations in the surrounding aquifer soil cores
- TCE concentrations in the vadose zone soil cores
- TCE concentrations in surface emissions to the atmosphere
- TCE concentrations in the confined aquifer.

5.3.2.1 Potential for DNAPL Migration to the Surrounding Aquifer

Hydraulic gradients (water-level measurements). As mentioned in Section 5.2, pre-demonstration *hydraulic gradients* in the Launch Complex 34 aquifer are relatively flat in all three stratigraphic units. There was no noticeable change in hydraulic gradient in the resistive heating plot and vicinity *during* the demonstration, although the monitoring wells inside the resistive heating plot were not available for monitoring at all times. On the other hand, water-level measurements collected in April 2000 (see Figures 5-18 to 5-20) in the surrounding wells showed a sharp hydraulic gradient emanating radially from the ISCO plot, especially in the Lower Sand Unit. These measurements were taken while the third and final oxidant injection was under way in the Lower Sand Unit of the ISCO plot. During the April 2000 event, the gradient was not as strong in the shallow and intermediate wells, indicating that the Middle Fine-Grained Unit acts as a conspicuous hydraulic barrier. Residual DNAPL cannot migrate due to hydraulic gradient alone, no matter how strong. However, if there was *mobile* DNAPL present in the aquifer, strong injection pressures could have caused DNAPL movement from the ISCO or steam injection plot. Also, the heating in the resistive heating plot could have caused some of the residual DNAPL in the plot to become more mobile (heating reduces surface tension of the DNAPL causing it to move more easily) and migrate under the influence of these externally generated hydraulic gradients. In general, the strong hydraulic gradients originating from the ISCO plot makes evaluation of DNAPL migration in the resistive heating plot difficult.

Temperature measurements conducted with a downhole thermocouple in May 2000 are shown in Figures 5-6 to 5-8 for the shallow, intermediate, and deep wells in the resistive heating plot and vicinity. As expected, the largest increase in temperature was in the middle of the resistive heating plot (where the electrodes were installed). Temperature increased noticeably in all five perimeter well clusters (PA-10, IW-17, PA-15, PA-7, and PA-2) but remained at baseline (pre-demonstration) levels in the more distant wells. Post-demonstration soil cores collected around the resistive heating plot and inside the building also were warm, indicating that heat generated in the resistive heating plot had spread to the surrounding regions through conduction and/or convection. The temperature data indicate that DNAPL in the resistive heating plot and vicinity had the potential to be mobilized by hydraulic gradients. At ambient temperatures, residual DNAPL cannot be mobilized, but heating reduces surface tension of the DNAPL making it more amenable to movement in the aquifer. This could be one explanation for the DNAPL that appeared in PA-2I and PA-2D wells, after the resistive heating demonstration had commenced. Thermally induced convection could assist such movement. Alternatively, heat-vaporized TCE migrating upward in the Lower Sand Unit could have encountered the Middle Fine-Grained Unit and migrated sideways to the surrounding aquifer. It is difficult to interpret the true effect of a mix of thermal and hydraulic gradients in the resistive heating plot resulting from the demonstration.

Migration of ground water and dissolved ground-water constituents from the ISCO plot are exemplified by the movement of **potassium ion** in the aquifer, as shown in Figures 5-21 to 5-23. Potassium, originating from the injected oxidant, acts as a conservative tracer for tracking ground-water movement. Figures 5-21 to 5-23 show the excess potassium (above pre-demonstration levels) in the ground water at Launch Complex 34. Because more monitoring wells are present on the western side of the ISCO plot, movement seems to be occurring to the west; however, similar ground-water transport probably occurred in all directions from the plot. This migration of ground water and dissolved species from the ISCO plot is an important aspect of injecting oxidant without concomitant extraction or hydraulic control, and may need to be reviewed on a site-specific basis. In summary, both technologies, the resistive heating and ISCO treatments, created conditions conducive to DNAPL migration.

TCE and other CVOCs are among the dissolved species that migrated from the resistive heating plot as indicated by the TCE measurements in perimeter and distant wells (see Appendix C). Figures 5-24 to 5-26 show the TCE trends observed in the **perimeter wells**. TCE levels in the perimeter wells IW-17S and IW-17I (on the west side of the resistive heating plot) rose sharply when the

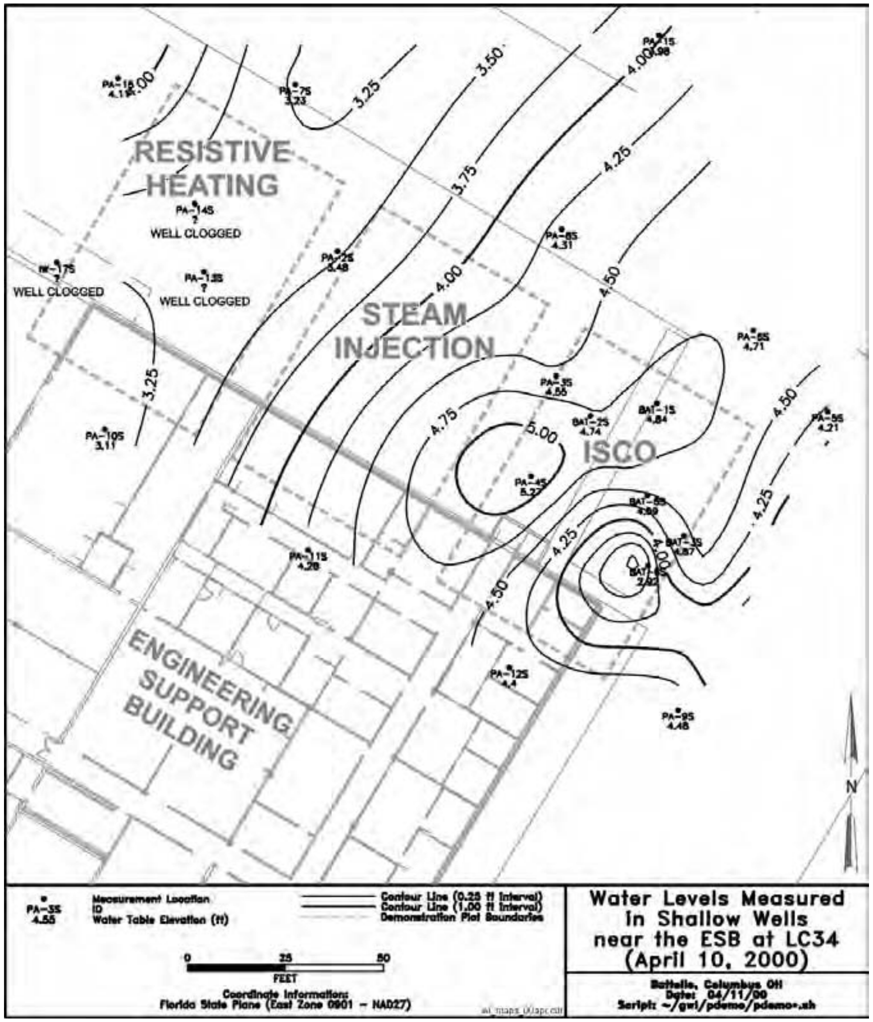


Figure 5-18. Water Levels Measured in Shallow Wells near the Engineering Support Building at Launch Complex 34 (April 10, 2000)

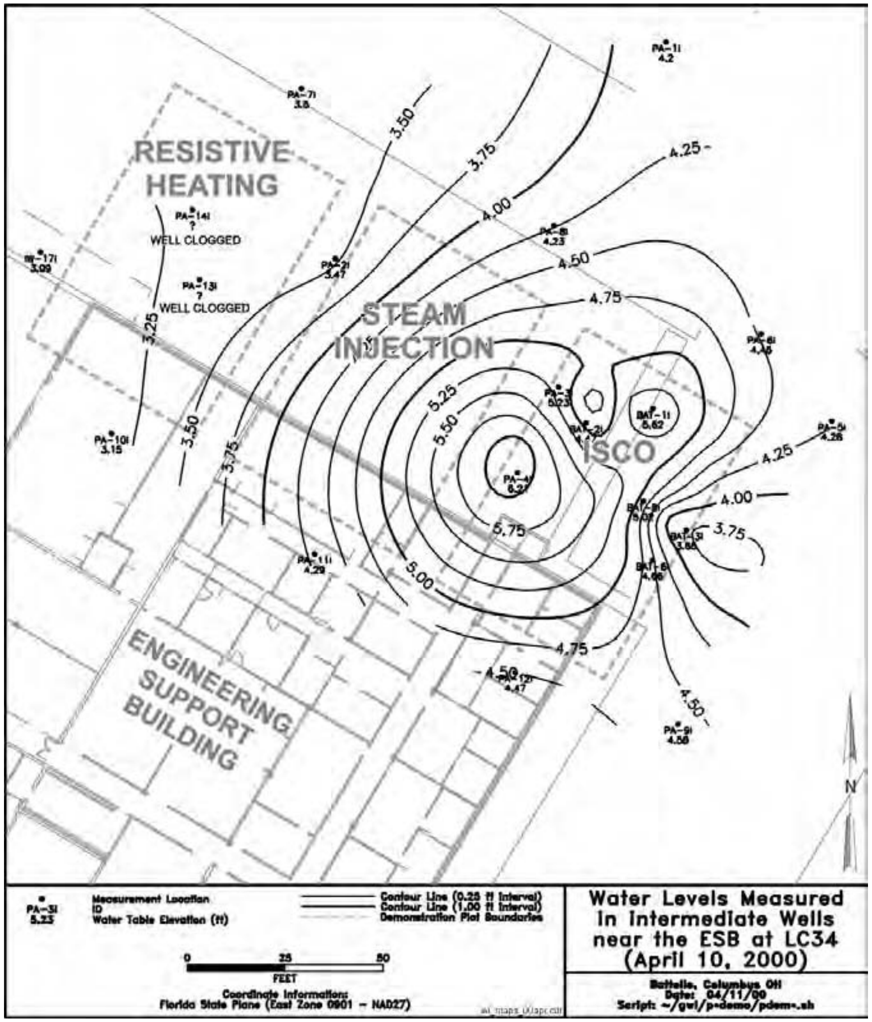


Figure 5-19. Water Levels Measured in Intermediate Wells near the Engineering Support Building at Launch Complex 34 (April 10, 2000)

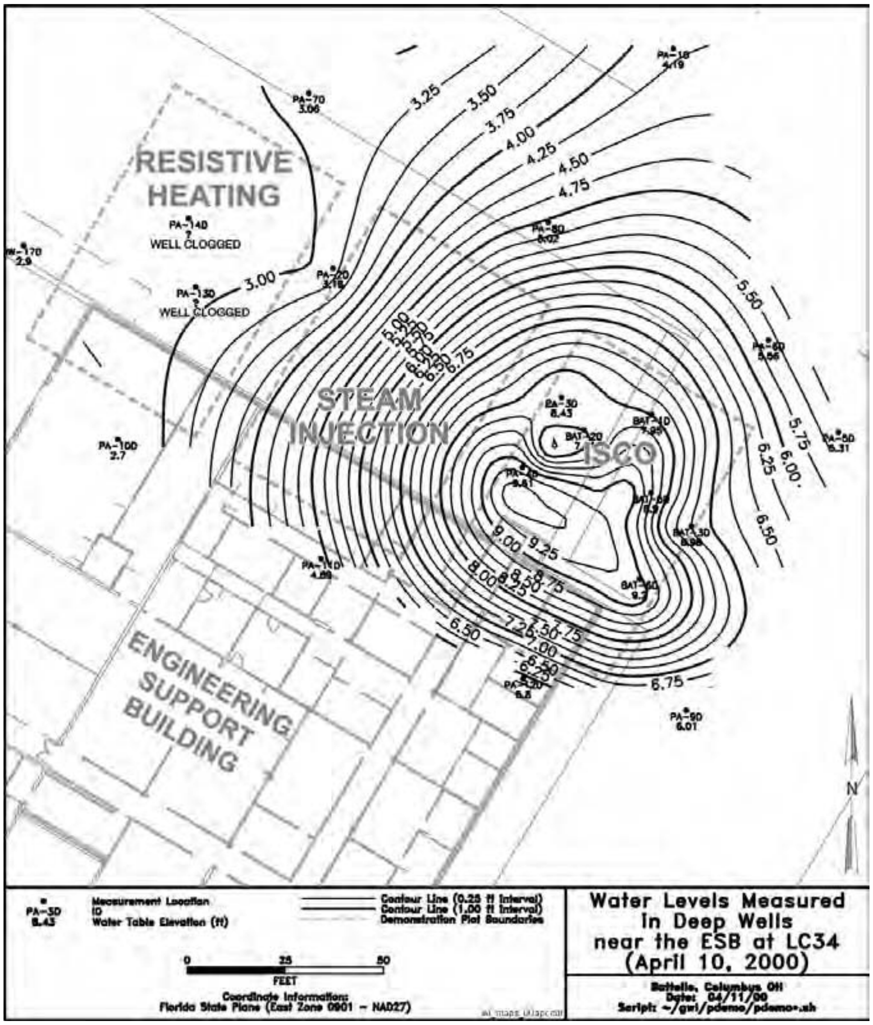


Figure 5-20. Water Levels Measured in Deep Wells near the Engineering Support Building at Launch Complex 34 (April 10, 2000)

resistive heating treatment started and the increase was sustained through the end of the demonstration. In other perimeter wells, TCE levels either declined sharply or showed a mild increase. A sharp temporary increase in TCE concentrations in the monitoring wells would signify that dissolved-phase TCE has migrated. A sharp sustained increase may signify that DNAPL has redistributed within the plot or outside it.

Figure 5-27 shows the **TCE** trends observed in **distant well** clusters PA-8 and PA-1. PA-8 is closer to the resistive heating plot to the northeast of the plot. PA-1 is further away towards the north-northeast side. The PA-8 cluster showed a significant increase in TCE concentrations in the shallow and deep wells. After the ISCO and resistive heating treatments started, DNAPL was observed for the first time in a distant well, PA-11D, as well as perimeter wells PA-2I, and PA-2D, all of which are on the east side of the resistive heating plot, near remaining DNAPL after the treatment shown in Figure 5-5, and on the west side of the ISCO plot. DNAPL had not been previously found in any of the monitoring wells before the demonstration. This indicates that some free-phase TCE movement occurred in the aquifer due to the application of the two technologies. It is unclear which of the two technologies contributed to the DNAPL movement and whether or not this DNAPL was initially in mobile or residual form. Mobile DNAPL could have moved under the influence of the sharp hydraulic gradient induced by the oxidant injection pressures alone. Residual DNAPL, by nature, would not be expected to move.

When the ground-water data indicated that DNAPL movement had occurred, additional post-demonstration **soil cores** were collected from areas **surrounding the resistive heating plot** (see Figure 4-3 in Section 4). The additional soil coring locations surrounding the resistive

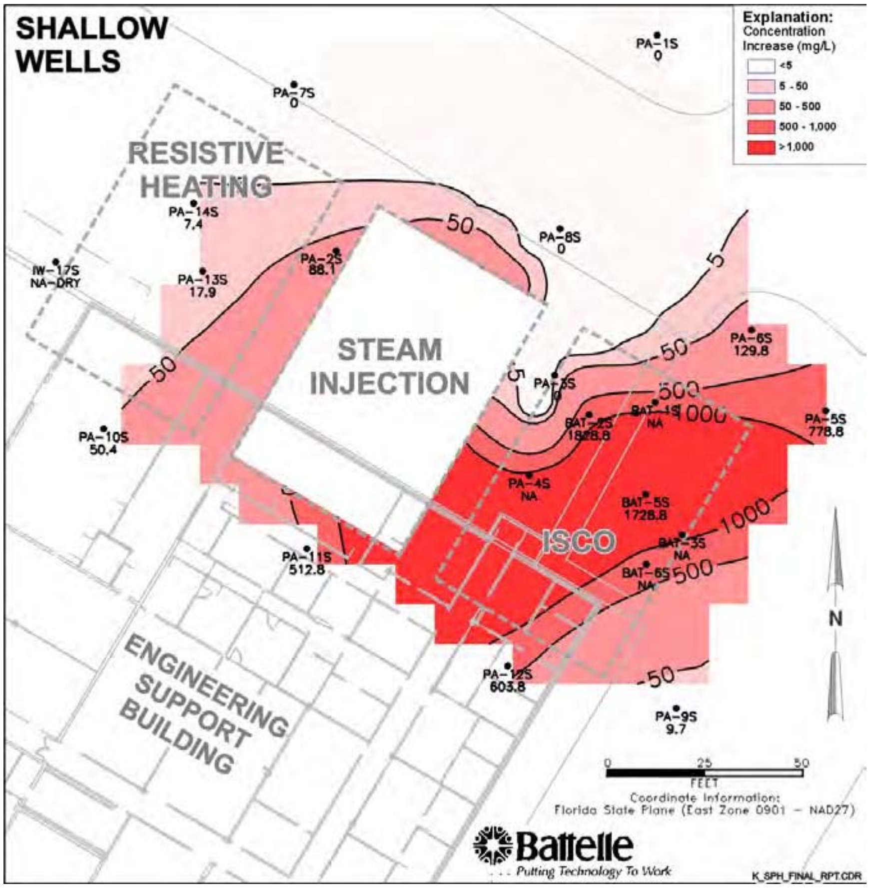


Figure 5-21. Distribution of Potassium (K) Produced by ISCO Technology in Shallow Wells near the Engineering Support Building at Launch Complex 34 (April 2000)

heating plot were selected because these were the only locations in the immediate vicinity of the resistive heating plot where pre-demonstration soil core data were available for comparison. As shown in Figure 5-28, in none of these perimeter soil samples was there a noticeable increase in TCE or DNAPL concentration following the demonstration. The sampling density of the soil cores surrounding the plot is not as high as the sampling density inside the plot; therefore, the effort was more exploratory than definitive. None of these soil cores showed any noticeable increase in DNAPL levels (TCE greater than 300 mg/kg), although the DNAPL already present under the Engineering Support Building and on the east side of the plot would tend to mask the appearance of fresh DNAPL and make it difficult to identify DNAPL migration in these directions.

To evaluate the possibility of TCE-DNAPL migration to the **vadose zone**, all pre- and post-demonstration **soil cores** in the resistive heating plot included soil samples collected at 2-ft intervals in the vadose zone. As seen in Figure 5-25, there was no noticeable deposition of TCE in the vadose zone soil due to the resistive heating treatment.

Surface emission tests were conducted as described in Appendix F to evaluate the possibility of solvent losses to the atmosphere. As seen in Table 5-14, there was a noticeable increase in TCE concentrations between surface emission samples collected in the resistive heating plot (or around the plenum) and at background locations at various times during the demonstration (see Figure 5-29 for the samples locations). This indicates that there was some loss of TCE to the ambient air around the plot during the heat treatment and that the vapor extraction system was not as efficient at controlling vapor losses as would be desirable. The relatively shallow vadose zone could be one of the factors driving the difficulty in vapor capture. In addition, the vadose zone completely disappeared during hurricane events in September 1999, as the water table rose to ground surface (the resistive heating plot is at a topographic low point at Launch Complex 34).

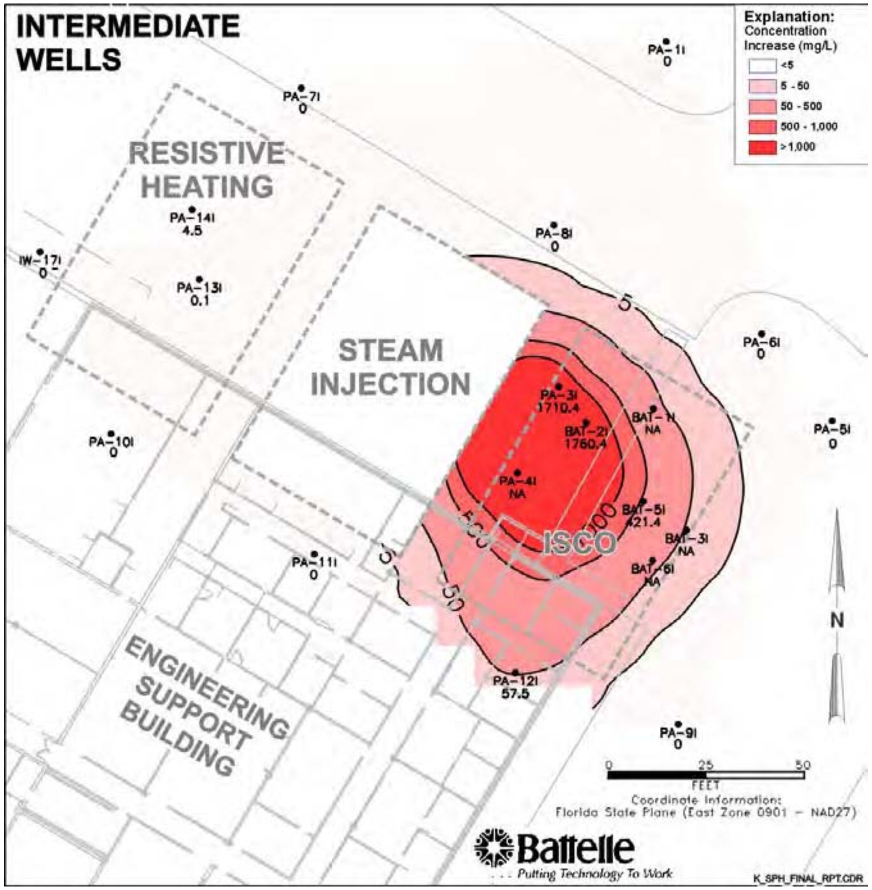


Figure 5-22. Distribution of Potassium (K) Produced by ISCO Technology in Intermediate Wells near the Engineering Support Building at Launch Complex 34 (April 2000)

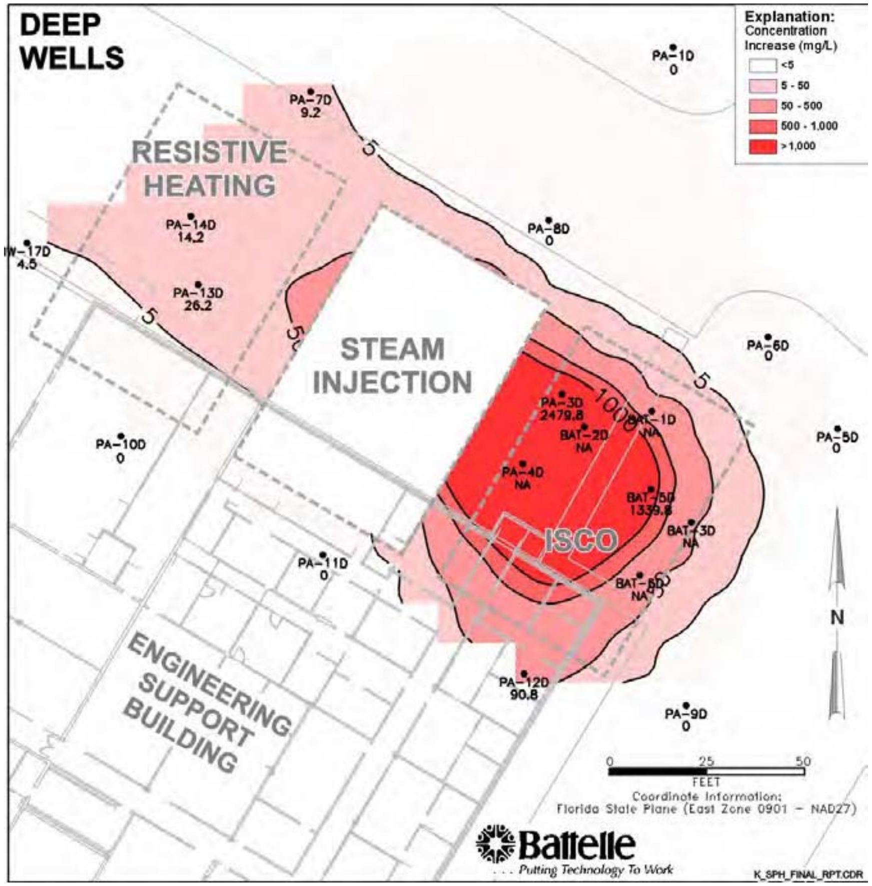


Figure 5-23. Distribution of Potassium (K) Produced by ISCO Technology in Deep Wells near the Engineering Support Building at Launch Complex 34 (April 2000)

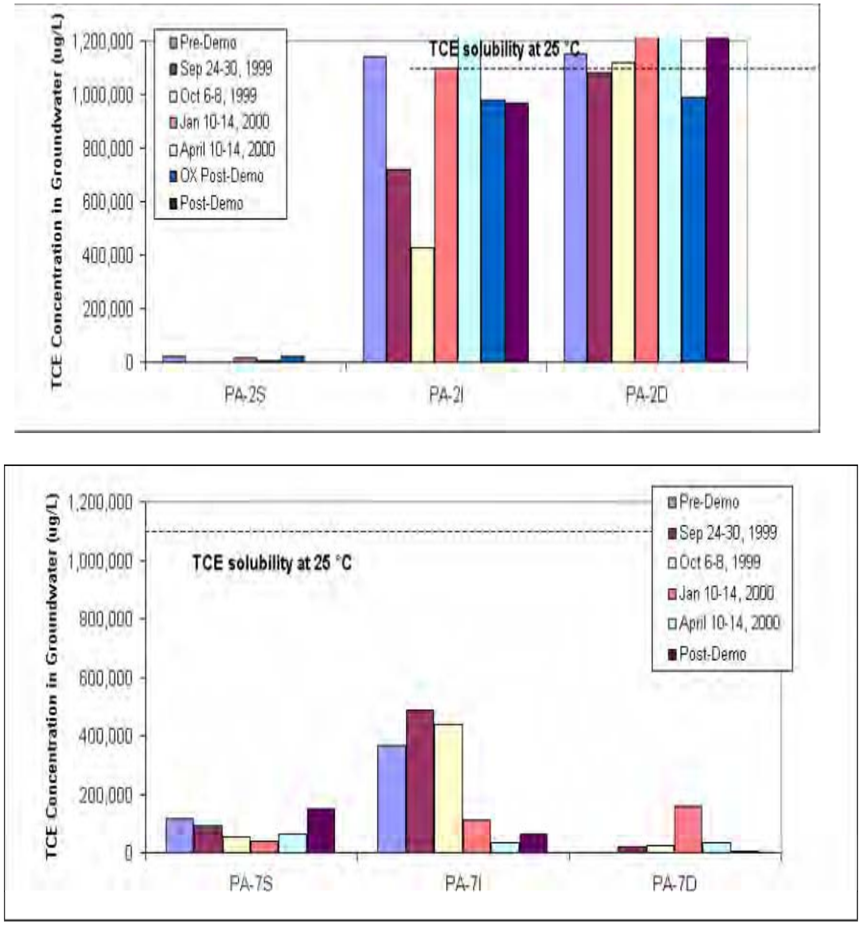


Figure 5-24. Dissolved TCE Levels (µg/L) in Perimeter Wells on the Eastern (PA-2) and Northern (PA-7) Side of the Resistive Heating Plot

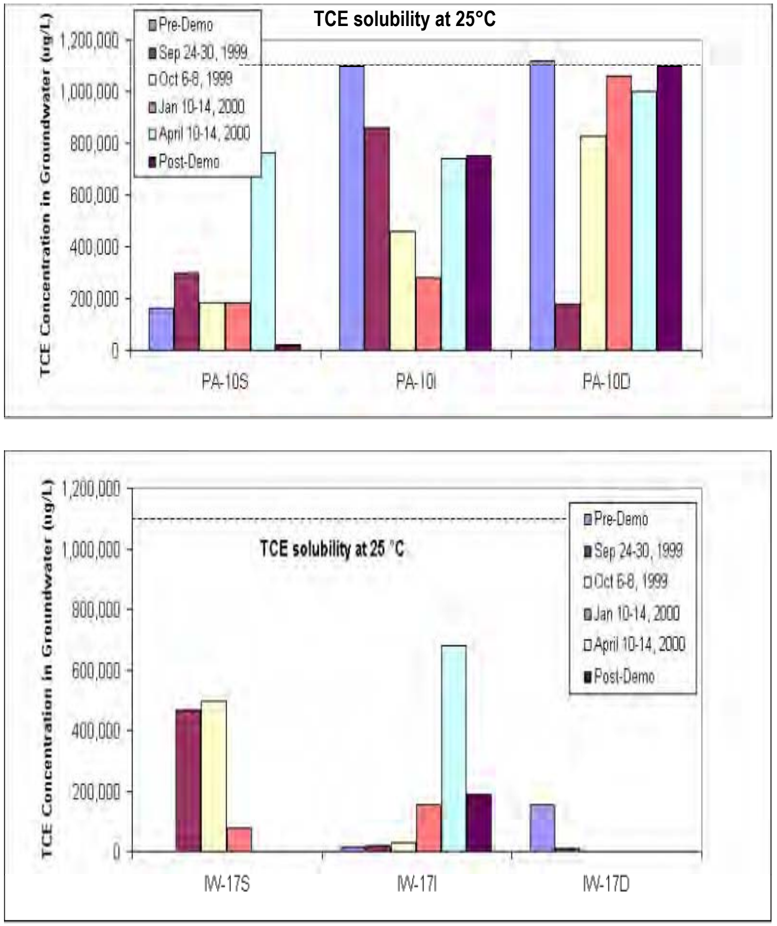


Figure 5-25. Dissolved TCE Levels (µg/L) in Perimeter Wells on the Southern and Western Sides of the Resistive Heating Plot

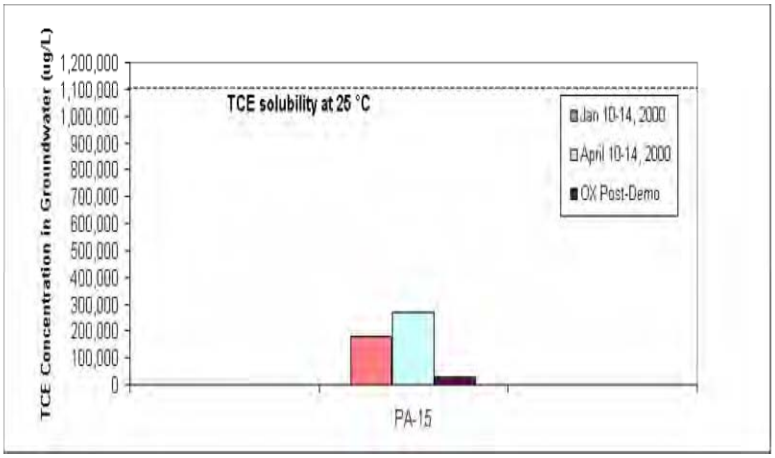


Figure 5-26. Dissolved TCE Levels (µg/L) in Perimeter Well (PA-15) on the Western Side of the ISCO Plot

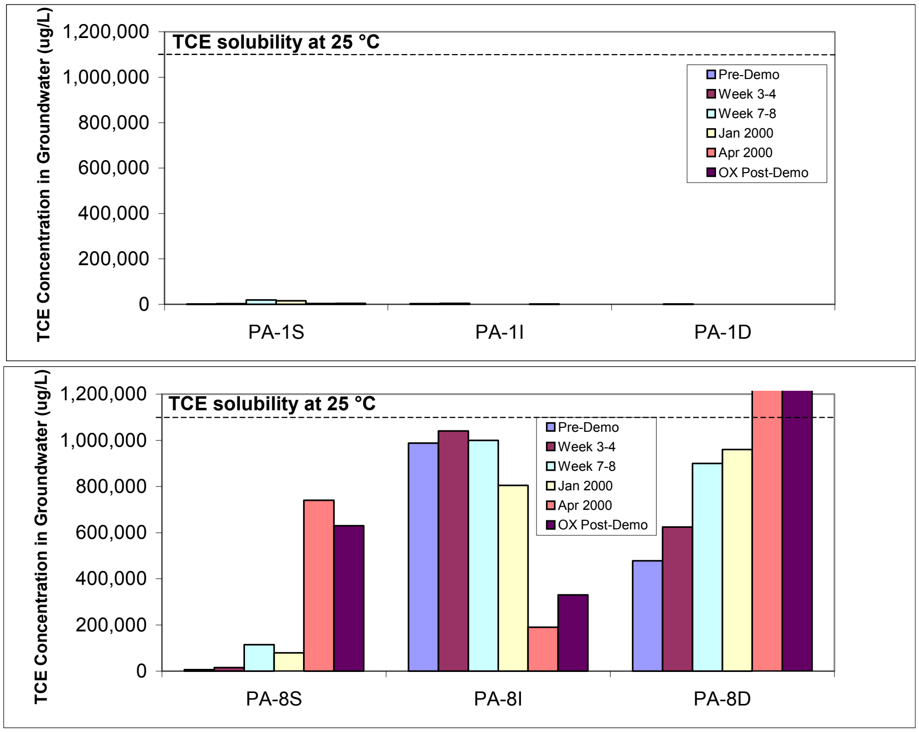


Figure 5-27. Dissolved TCE Levels (µg/L) in Distant Wells (PA-1 and PA-8) on the Northeastern Side of the ISCO Plot

During these hurricanes, it is probable that shallow ground water (laden with TCE) from the plot migrated into a ditch on the northwest side of the plot. Elevated TCE levels were subsequently found in ponded **surface water** samples collected along this ditch by FSU. However, the additional post-demonstration soil cores (LC34B309, LC34B214 and LC34B314) collected along the ditch did not reveal any TCE at DNAPL levels. Therefore, it is likely that the TCE that migrated during the hurricanes was mostly in the dissolved phase and not DNAPL. The ditch is dry during most times of the year and no surface water was present during the post-demonstration monitoring event.

5.3.2.2 Potential for DNAPL Migration to the Lower Clay Unit and Semi-Confined Aquifer

The geologic logs of the three confined aquifer wells are provided in Appendix A. Their locations are shown in

Top Depth	Bottom Depth	PA-1 (mg/kg)	PA-201 (mg/kg)	PA-2 (mg/kg)	PA-202 (mg/kg)	PA-5 (mg/kg)	PA-205 (mg/kg)	LC34B14 (mg/kg)	LC34B214 (mg/kg)	LC34B314 (mg/kg)
0	2	NA	8.6	NA	2	NA	ND	NA	ND	ND
2	4	NA	ND	NA	1	NA	ND	NA	ND	ND
4	6	NA	0.7	NA	ND	NA	ND	NA	ND	ND
6	8	NA	1.2	NA	2	NA	ND	NA	ND	ND
8	10	NA	ND	NA	ND	NA	0.6	NA	ND	5
10	12	NA	ND	NA	2	NA	ND	ND	ND	5
12	14	NA	1.5	NA	1	NA	3.4	ND	ND	6
14	16	NA	4.6	NA	0	2.5	ND	ND	11	12
16	18	NA	0.9	NA	694	1.0	136	ND	4	16
18	20	NA	2.6	4,513	21	5.4	127	ND	1	3
20	22	NA	6.6	316	156	2	41	ND	10	ND
22	24	NA	12.8	275	598	91	27	ND	3	ND
24	26	NA	ND	336	798	193	65	ND	ND	ND
26	28	NA	ND	293	346	125	58	ND	ND	ND
28	30	NA	ND	223	3,858	15	39	ND	ND	ND
30	32	NA	ND	NA	13,100	73	31	ND	ND	ND
32	34	NA	ND	2,570	2,039	1.8	ND	ND	ND	ND
34	36	0.3	ND	814	4,886	NA	ND	ND	ND	ND
36	38	NA	ND	218	681	1.1	6.3	ND	ND	1
38	40	NA	ND	271	416	2.3	19.8	ND	ND	ND
40	42	2.9	ND	2,792	NA	8.2	48.8	ND	NA	ND
42	44	NA	ND	1,096	444	27	5.1	ND	NA	0
44	46	NA	ND	NA	472	8.2	NA	ND	NA	NA

Figure 5-28. Pre- and Post-Demonstration TCE Concentrations (mg/kg) for Resistive Heating Perimeter Soil Samples (page 1 of 3)

Top Depth	Bottom Depth	PA-6 (mg/kg)	PA-206 (mg/kg)	PA-7 (mg/kg)	PA-207 (mg/kg)	PA-8 (mg/kg)	PA-208 (mg/kg)	LC34B17 (mg/kg)	LC34B217 (mg/kg)	LC34B39 (mg/kg)	LC34B239 (mg/kg)
0	2	NA	NA	NA	1.3	NA	3.5	NA	ND	NA	0.8
2	4	NA	1.7	NA	4.1	NA	1.2	NA	ND	NA	0.4
4	6	NA	ND	NA	1.1	NA	0.9	NA	1	NA	0.3
6	8	NA	ND	NA	1.0	NA	ND	NA	1	NA	1.3
8	10	NA	ND	NA	3.8	NA	ND	NA	13	NA	6
10	12	NA	2.3	NA	8.6	NA	0.3	NA	11	NA	12
12	14	NA	1.6	NA	10	NA	ND	NA	14	NA	9
14	16	0.3	0.5	0.5	89	0.9	ND	NA	6	NA	4
16	18	1.9	35	1.4	89	0.5	ND	NA	ND	NA	9
18	20	21	124	0.4	5	1.1	31	NA	ND	NA	16
20	22	83	86	2.9	12	38	32	0.1	8	NA	5
22	24	NA	144	75	2.6	6.3	102	0.0	96	NA	346
24	26	179	202	6.9	ND	175	255	0.0	160	0.1	222
26	28	255	237	46	1.6	77	108	0.0	223	NA	298
28	30	164	233	6.1	1.1	67	32	ND	67	NA	358
30	32	131	81	0.5	29	32	92	ND	27	NA	289
32	34	137	45	0.3	18.4	53	58	ND	NA	NA	314
34	36	112	189	0.1	ND	41	34	ND	ND	NA	247
36	38	39	170	1.2	7.9	1	44	ND	ND	NA	284
38	40	5	214	0.2	ND	2	138	ND	NA	NA	158
40	42	56	71	0.7	ND	21	147	ND	ND	0.1	NA
42	44	74	0.7	NA	ND	95	261	0.062	NA	0.1	267
44	46	33	0.3	0.1	0.8	115	234	0.017	NA	0.2	265

Figure 5-28. Pre- and Post-Demonstration TCE Concentrations (mg/kg) for Resistive Heating Perimeter Soil Samples (page 2 of 3)

Top Depth	Bottom Depth	PA-9 (mg/kg)	PA-209 (mg/kg)	PA-11 (mg/kg)	PA-211 (mg/kg)	PA-12 (mg/kg)	PA-212 (mg/kg)	LC34B09 (mg/kg)	LC34B209 (mg/kg)	LC34B309 (mg/kg)
0	2	NA	NA	NA	3.3	NA	ND	NA	ND	ND
2	4	NA	ND	NA	NA	NA	0.8	NA	ND	ND
4	6	NA	ND	NA	2.5	NA	0.9	NA	1	ND
6	8	NA	ND	NA	3.5	NA	1.0	NA	3	ND
8	10	NA	ND	NA	0.5	NA	1.4	NA	18	ND
10	12	NA	3.6	NA	1	NA	2.2	NA	28	ND
12	14	NA	36	NA	14	NA	ND	NA	50	3
14	16	6	51	NA	27	NA	ND	ND	28	ND
16	18	92	56	NA	32	4	ND	ND	3	ND
18	20	156	81	5.5	3.2	24	ND	ND	23	ND
20	22	188	89	NA	3.4	30	ND	0.001	53	ND
22	24	205	46	207	3,332	31	87	0.004	41	ND
24	26	9.1	37	250	123	154	84	0.069	6	ND
26	28	58.4	ND	228	958	126	305	0.1	1	ND
28	30	14.7	ND	236	186	201	327	0.025	3	ND
30	32	0.6	ND	185	468	NA	307	0.009	1	ND
32	34	0.2	2.9	483	300	130	209	0.007	3	ND
34	36	3.0	1.3	363	208	125	176	ND	ND	ND
36	38	0.1	7.1	142	206	178	314	ND	4	ND
38	40	1.6	61	NA	961	NA	123	ND	ND	ND
40	42	NA	61	NA	2,357	73	149	0.001	ND	ND
42	44	41.7	NA	NA	241	98	97	ND	2	ND
44	46	1.2	NA	NA	NA	196	NA	ND	NA	ND

LC34B2XX and PA-2XX: Post-demonstration characterization coring IDs.
NA: Not available.
ND: Not detected.
Color in the chart represents the soil sample color observed during the soil sample collection.
Solid horizontal lines demarcate the Middle Fine-Grained Unit.

Figure 5-28. Pre- and Post-Demonstration TCE Concentrations (mg/kg) for Resistive Heating Perimeter Soil Samples (page 3 of 3)

Table 5-14. Surface Emissions Results from Resistive Heating Treatment Demonstration

Sample ID	Sample Date	TCE ppb (v/v)	Sample ID	Sample Date	TCE ppb (v/v)
Pre-Demonstration (Baseline Data Sampled from Steam Injection Plot)					
CP-SE-1	11/17/1999	< 0.39	CP-SE-3	11/17/1999	< 0.41
CP-SE-2	11/17/1999	< 0.39			
During Demonstration					
SPH-SE-1	10/08/1999	2.1	SPH-SE-8	01/18/2000	78
SPH-SE-2	10/08/1999	3.6	SPH-SE-9	01/18/2000	35
SPH-SE-3	10/08/1999	2.0	SPH-SE-10	04/11/2000	0.93
SPH-SE-4	10/22/1999	**13,000**	SPH-SE-11	04/11/2000	0.67
SPH-SE-5	10/22/1999	**12,000**	SPH-SE-12	04/11/2000	<0.37
SPH-SE-6	10/22/1999	**13,000**	SPH-SE-13	04/11/2000	**1,300**
SPH-SE-7	01/18/2000	23			
Post-Demonstration					
SPH-SE-21	08/30/2000	<0.42	SPH-SE-27	11/30/2000	**3,100**
SPH-SE-22	08/30/2000	0.61	SPH-SE-28	11/30/2000	**10,000**
SPH-SE-23	08/30/2000	<870	SPH-SE-29	12/01/2000	**11,000**
SPH-SE-24	08/31/2000	500	SPH-SE-30	12/02/2000	9.0
SPH-SE-25	09/01/2000	59	SPH-SE-31	12/02/2000	0.71
SPH-SE-26	09/01/2000	17	SPH-SE-32	12/04/2000	<0.40
Background			*Ambient Air at Shoulder Level*		
DW-SE-1	10/01/1999	< 0.42	SPH-SE-14	05/09/2000	<0.39(a)
DW-SE-2	10/08/1999	< 0.44	SPH-SE-15	05/09/2000	<0.39(a)
DW-SE-3	10/25/1999	0.44	SPH-SE-C27	09/01/2000	<0.88
DW-SE-4	10/22/1999	**6,000**(b)	DW-C1	04/11/2000	2.1(c)
DW-SE-5	01/17/2000	< 0.38	DW-C2	05/09/2000	<0.39
DW-SE-6	04/11/2000	0.43	DW-C3	05/09/2000	<0.39
DW-SE-7	04/11/2000	0.86	DW-11	08/31/2000	13
DW-SE-8	04/11/2000	0.79	DW-12	09/01/2000	<27
DW-SE-36	12/06/2000	<0.40	DW-C21	08/31/2000	0.86(c)
DW-SE-37	12/06/2000	0.49	DW-C22	09/01/2000	<0.58(c)
DW-SE-38	12/07/2000	<0.40			

ppb (v/v): parts per billion by volume.

(a) SPH-SE-14/15 samples were collected at an ambient elevation east and west edge of the resistive heating plot without using an air collection box.

(b) Background sample (10/22/1999) was collected immediately after SPH-SE-6 sample (the last sample for the sampling set in October 1999), which had an unexpectedly high concentration of 13,000 ppbv. This may indicate condensation of TCE in the emissions collection box at levels that could not be removed by the standard decontamination procedure of purging the box with air for two hours. In subsequent events (1/17/2000 background), special additional decontamination steps of cleaning the box with methanol and air dry were adapted to minimize carryover.

(c) A Summa canister was held at shoulder level to collect an ambient air sample to evaluate local background air.

Figure 4-7 in Section 4.3.1. Table 5-15 shows the depths and thicknesses of the Lower Clay Unit (aquitard) and the screened intervals of the wells installed. Figure 5-30 is a geologic cross section across the three test plots showing the varying thickness of the aquitard. The aquitard is thinnest in the resistive heating plot, where it is only around 1.5 ft thick. The thickness of the aquitard increases in the eastward and northward directions.

Split-spoon samples of the Lower Clay Unit show it to be a medium gray-colored clay with moderate to high plasticity. The clay is overlain by a silt zone which in turn is overlain by sand. The entire sand-silt-clay sequence appears to be gradational and fining downward with respect to grain size. In PA-21, the overlying sand and silt intervals appeared to be more contaminated (PID reading over 2,000 ppm). The clay itself was generally less contaminated, but lower PID readings in the clay may be due to the fact that volatilization of organic contaminants in clayey soils occurs more slowly. Sandier soils were encountered directly below the confining unit. Only at the PA-20 well did soils underlying the confining unit appear to be clean.

Soil samples were collected for lab analysis from each split spoon. Care was taken to collect soil samples of each 2-ft interval from the retrieved soil core. Multiple samples were collected in cases where both clays and sand were recovered in a spoon. PID readings exceeded 1,000 ppm (or more) at both the PA-21 and PA-22 locations both above and below the confining unit. Visual observations of clay samples indicated that the clay has low permeability.

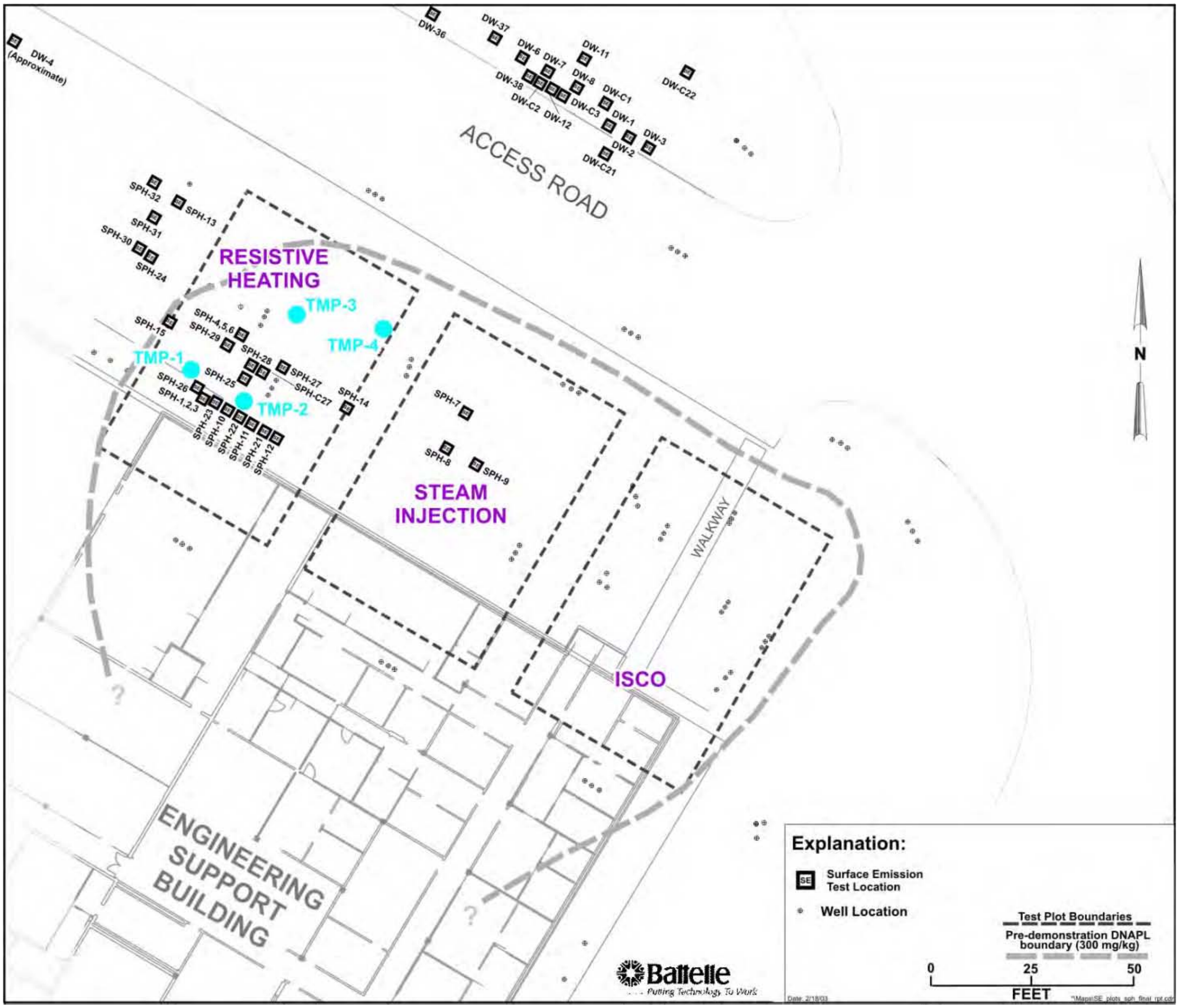


Figure 5-29. Location Map for Surface Emissions Test

Table 5-16 and Figure 5-31 show the vertical distribution of the TCE analysis results of the soil samples collected at depths of approximately 40 to 60 ft bgs; the lower clay unit occurs at approximately 46 ft bgs in the resistive heating plot. The soil borings SB-50, SB-51, and SB-52 are the borings done for wells PA-20, PA-21, and PA-22 (see Figure 4-7 in Section 4.3.1). Soil boring SB-50 was conducted in the parking lot and did not show any concentrations approaching the DNAPL threshold of 300 mg/kg at any depth. Soil boring SB-51 was conducted in the ISCO plot; this boring indicated the presence of DNAPL in the Lower Sand Unit and Lower Clay Unit, but relatively low levels of TCE in the confined aquifer. Soil boring SB-52, in the resistive heating plot, showed the presence of DNAPL in the Lower Clay Unit, the semi-confining unit from the aquifer below; TCE levels were as high as 40,498 mg/kg in the semi-confined aquifer (56-58 ft bgs) at this location. Previously, no monitoring was done in the semi-confining layer or in the semi-confined aquifer before the demonstration because of NASA's concern about breaching the relatively thin aquitard. Subsequently, these three wells were drilled because nonintrusive (seismic) monitoring indicated the possibility of DNAPL being present in the semi-confined aquifer (Resolution Resources, 2000). Because there is no information regarding the state of the confined aquifer before the demonstration, it is unclear whether the DNAPL had migrated to the semi-confined aquifer before

Table 5-15. Confined Aquifer Well Screens and Aquitard Depth

Well ID	Screened Interval (ft bgs)	Depth where Aquitard was Encountered (ft bgs)	Thickness of Aquitard (ft)
PA-20 (North of steam injection plot in parking lot)	55-60	45.5	3
PA-21 (In ISCO plot)	55-60	44.8	2.8
PA-22 (In resistive heating plot)	55-60	45.8	3[(a)]

(a) The confining unit clay contained thin sand lenses. Three ft is the overall thickness, including the interspersed sand lenses. The effective thickness of the aquitard is approximately 1.5 ft.

Table 5-16. TCE Concentrations in Deep Soil Borings at Launch Complex 34

Approximate Depth (ft bgs)	TCE (mg/kg)[(a)]		
	SB-50 (PA-20)	SB-51 (PA-21)	SB-52 (PA-22)
39-40		66	
40-41			20
41-42	174	6,578	
42-43			21
43-44	72		
44-45		3,831	37
45-46	19	699	138
46-47	39	2,857	
47-47.5			
47.5-48			
48-49	5	46	
49-50			367
50-51	1	49	473
51-52			707
52-53	<1	3	
53-54			
54-55	<1	<1	8,496; 10,700
55-56			
56-57	2	<1	40,498
57-58			
58-59	<1	<1	122
59-60			

(a) Shaded cells represent the Lower Clay Unit between the surficial and confined aquifers.

or during the demonstration. Heating could have lowered the surface tension of DNAPL, making it easier to penetrate the Lower Clay Unit. However, given the strong electrical heating achieved in the Lower Sand Unit (of the surficial aquifer) that would tend to volatilize TCE and move it upward, the greater probability is that the DNAPL penetrated the Lower Clay Unit and entered the semi-confined aquifer before the demonstration. Although the Lower Clay Unit is approximately 3 ft thick in other parts of Launch Complex 34, it appears to contain sand lenses that reduce the effective thickness of the aquitard to approximately 1.5 ft near PA-22, under the resistive heating plot. Therefore, the barrier to gradual downward migration over time is geologically weaker in this region.

Table 5-17 summarizes the results of the CVOC analysis of the ground water from the semi-confined aquifer. CVOC measurements were taken on seven occasions over a one-year period to evaluate natural fluctuation. Ground-water samples from the semi-confined aquifer wells reinforce the soil sampling results. High levels of TCE approaching solubility (free-phase DNAPL) were observed in PA-22 where high soil concentrations were also observed (Yoon et al., 2002). In wells PA-20 and PA-21, relatively lower CVOC concentrations were measured, suggesting that the semi-confining clay layer is more competent in these areas and free phase contamination has not migrated into the semi-confined aquifer in this area. Elevated levels of *cis*-1,2-DCE (all three wells) and vinyl chloride (PA-21) also were found in the semi-confined aquifer wells. Overall, CVOC concentrations appear to be relatively stable over time in all three wells, namely, PA-20, PA-21, and PA-22 (see Figure 5-32).

Table 5-18 shows the field parameter measurements in the confined aquifer wells. Based on the relatively low DO and ORP levels, the semi-confined aquifer appears to be anaerobic. The ground water has a neutral-to-slightly-alkaline pH. The temperature was in the range of 26 to 28°C in PA-20 and PA-21, but in PA-22, which is below the resistive heating plot, the temperature during both events was elevated (44 to 49°C). The higher temperature in this well may be due to heat conduction from the resistive heating application in the surficial aquifer, although migration of heated water from the surficial aquifer through the thin Lower Clay Unit cannot be ruled out.

Table 5-19 shows the inorganic measurements in the semi-confined aquifer wells. The geochemical composition of the ground water appears to be relatively constant throughout the semi-confined aquifer, and is similar to that of the surficial aquifer.

Table 5-20 shows slug test results in the semi-confined aquifer wells. Slug tests were performed in July 2001 on the wells PA-20, PA-21, and PA-22. The recovery rates of the water levels were analyzed with the Bouwer (1989), Bouwer and Rice (1976), and Horslev (1951) methods for slug tests. The Bouwer and Rice methods may be used in confined aquifers where the top of the screen is well below the bottom of the confining layer, but are more suitable for unconfined aquifers. The Horslev method is more applicable in confined aquifers,

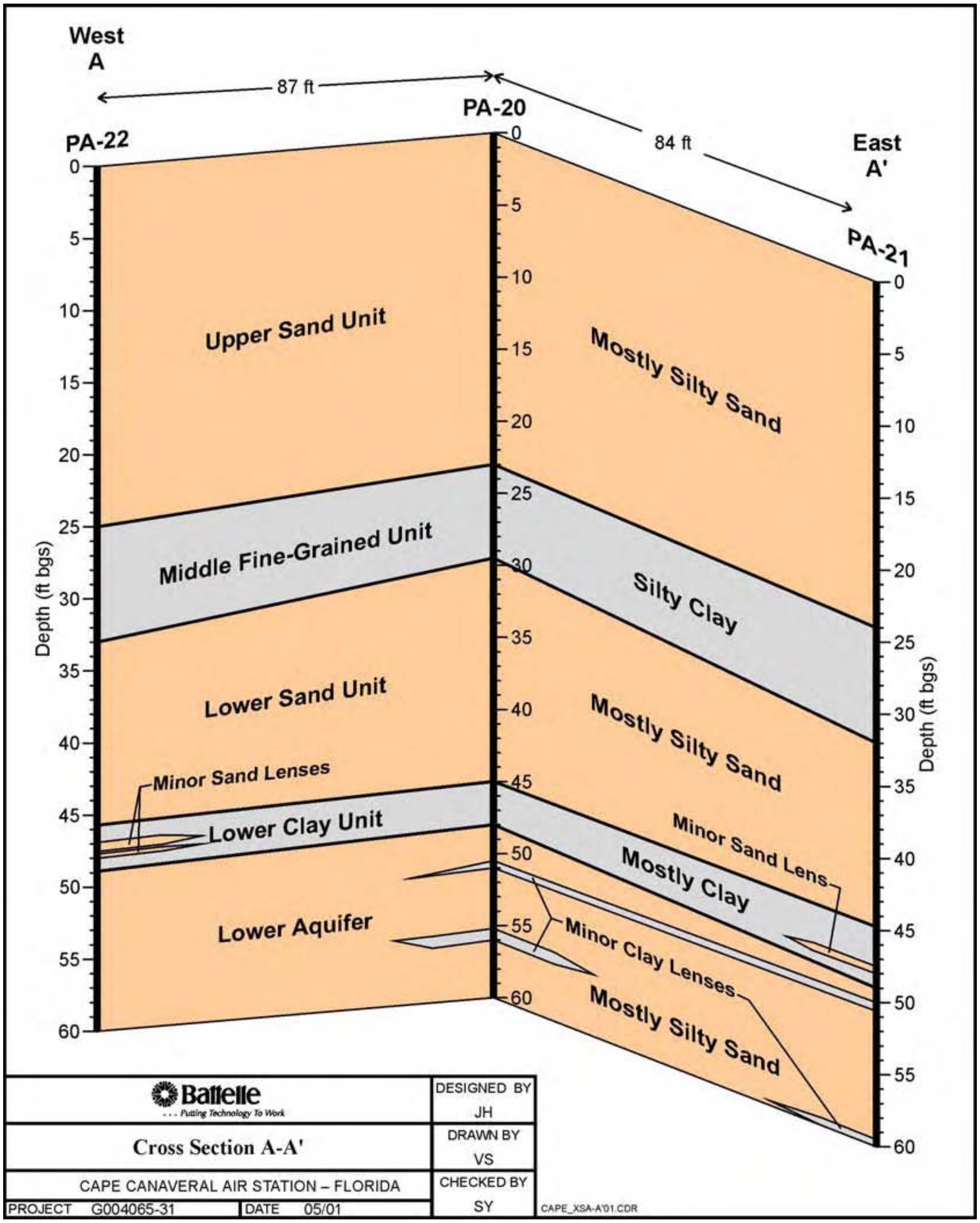


Figure 5-30. Geologic Cross Section Showing Lower Clay Unit and Semi-Confined Aquifer

but may fail to account for the effects of a sand pack. Overall, the hydraulic conductivity (K) estimates range from 0.4 to 29.9 ft/day. The Horslev method results are about two to four times higher than estimates using the Bouwer and Rice method. The replicate tests are similar, except for PA-20, where the Horslev method differed. It appears that the aquifer conductivity near well PA-20 is greater than near PA-21 and PA-22. The conductivity of wells PA-21 and PA-22 is lower and reflects the silty-clayey sands that were observed during drilling. The conductivities in the semi-confined aquifer are similar to the conductivities measured in the surficial aquifer wells.

Figure 5-33 shows the potentiometric map for water levels measured in April 2001 in the new semi-confined aquifer wells near the demonstration test plots at Launch Complex 34. Although very few wells are available to make a positive determination, the water levels measured

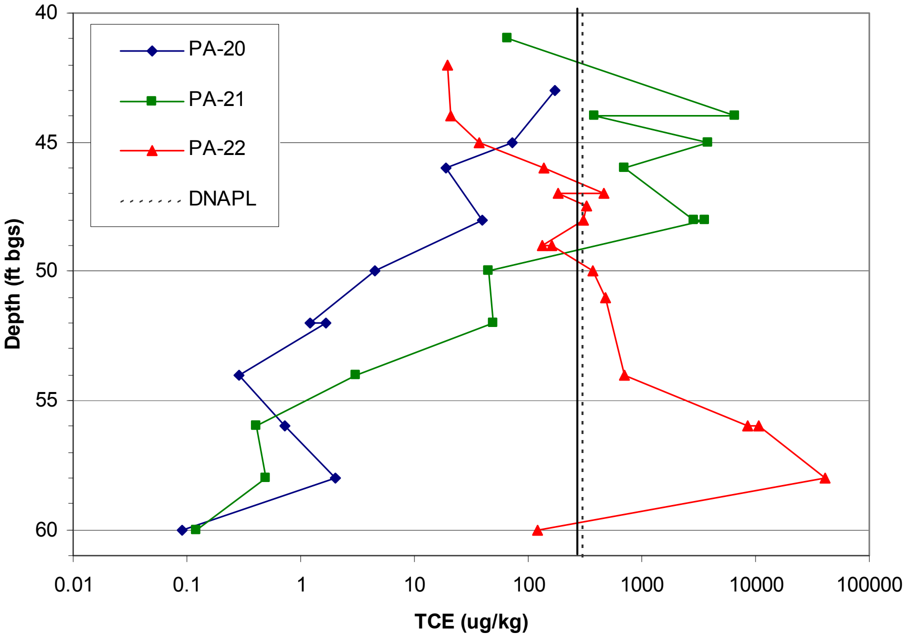


Figure 5-31. TCE Concentrations in Soil with Depth from Semi-Confined Aquifer Soil Borings

Table 5-17. TCE Concentrations in the Semi-Confined Aquifer Wells

Well ID	Feb 2001	Apr 2001	May 2002	Jun 2001	Aug 2001	Nov 2001	Feb 2002
PA-20	67.1	447	111	350	19	15	181
PA-20-DUP	58.4	N/A	N/A	N/A	N/A	N/A	N/A
PA-21	7,840	15,700	6,400	5,030	790	1,640	416
PA-22	736,000	980,000	877,000	801,000	1,000,000	1,110,000	1,240,000
PA-22-DUP	N/A	N/A	939,000	N/A	1,000,000	N/A	N/A

cis-1,2-DCE

Well ID	Feb 2001	Apr 2001	May 2002	Jun 2001	Aug 2001	Nov 2001	Feb 2002
PA-20	21.7	199	37.4	145	10	52	66
PA-20-DUP	18.5	N/A	N/A	N/A	N/A	N/A	N/A
PA-21	1,190	5,790	1,490	1,080	330	5,140	315
PA-22	8,130	8,860	11,000	11,900	12,000 J	14,900	13,300
PA-22-DUP	N/A	N/A	10,700	N/A	12,000 J	N/A	N/A

trans-1,2-DCE

Well ID	Feb 2001	Apr 2001	May 2002	Jun 2001	Aug 2001	Nov 2001	Feb 2002
PA-20	<0.1	1.45	0.24J	0.38	<1.0	0.48J	0.3J
PA-20-DUP	<0.1	N/A	N/A	N/A	N/A	N/A	N/A
PA-21	<1	51.7	6 J	5	<33	<10	2
PA-22	<100	<1,000	<1,120	<100	<17,000	<100	<1,000
PA-22-DUP	N/A	N/A	<1,090	N/A	<17,000	N/A	N/A

Vinyl Chloride

Well ID	Feb 2001	Apr 2001	May 2002	Jun 2001	Aug 2001	Nov 2001	Feb 2002
PA-20	<0.1	0.36J	<1.08	<0.1	<2.0	<0.10	<1.0
PA-20-DUP	<0.1	N/A	N/A	N/A	N/A	N/A	N/A
PA-21	<1	4.22	<22.2	<1	<67	1,050	<1.0
PA-22	<100	<1,000	<1,120	<100	<33,000	<100	260J
PA-22-DUP	N/A	N/A	<1,090	N/A	<33,000	N/A	N/A

N/A: Not analyzed.
J: Estimated value, below reporting limit.

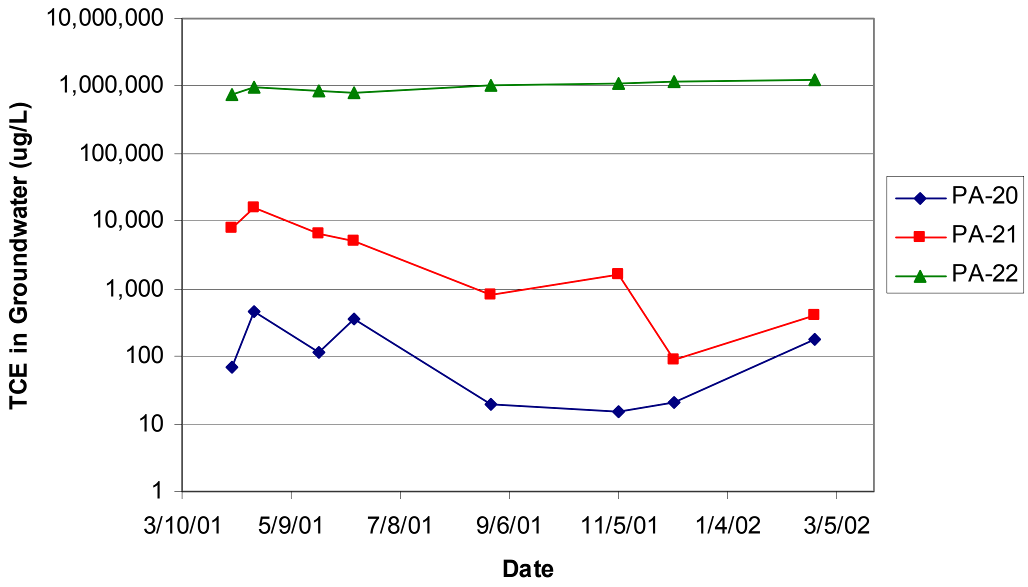


Figure 5-32. TCE Concentration Trend in Ground Water from Semi-Confined Aquifer

Table 5-18. Key Field Parameter Measurements in Semi-Confined Aquifer Wells

Well ID	Date	Temperature (°C)	DO (mg/L)	pH	ORP (mV)
PA-20	04/06/2001	27.2	0.65	7.8	67.4
PA-21	04/06/2001	28.4	0.05	8.84	30.2
PA-22	04/06/2001	48.9	0.36	6.77	39.1
PA-20	06/12/2001	26.2	0.42	7.21	–42.5
PA-21	06/12/2001	26.1	0.47	7.17	–36.5
PA-22	06/12/2001	44.4	0.78	7.25	–33.6

in four semi-confined aquifer wells (PA-20, PA-21, PA-22, and previously existing well IW-2D1, southeast from the test plots) indicate that there is an eastward or northeastward gradient, similar to the regional gradient observed in the surficial aquifer. The gradient and magnitude are summarized in Table 5-21.

Figure 5-34 displays vertical gradients from paired wells between nearby surficial aquifer wells and the newly installed wells (PA-20 to PA-22). A positive vertical gradient suggests upward flow from the deep aquifer to the surficial aquifer, which would inhibit downward migration of contamination. A negative gradient would promote downward migration. As shown in Figure 5-34, it appears that the vertical gradient fluctuates, beginning as an upward gradient when the wells were installed, changing to a downward gradient in the Fall of 2001, and finally recovering to an upward gradient.

In summary, the following were the key results and conclusions from the installation of three semi-confined aquifer wells at Launch Complex 34:

- Use of the two-stage (dual-casing) drilling and completion process led to the installation of three semi-confined aquifer wells that appeared to be sealed from the surficial aquifer above.
- At all three locations, the Lower Clay Unit occurs at approximately 45 ft bgs and is approximately 3 ft thick; at PA-22, located in the resistive heating plot, the Lower Clay Unit was found to contain sand lenses that appeared to reduce the effective thickness of the aquitard.

Table 5-19. Geochemistry of the Confined Aquifer

Well ID	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)
PA-20	71.8	<0.1	64	0.0145	180	664	114	1,400
PA-20-DUP	69.4	<0.1	62.8	0.0128	168	680	114	1,410
PA-21	74	<0.1	48	<0.01	196	553	134	1,310
PA-22	120	0.109	79.7	0.0534	276	802	122	1,840

Table 5-20. Results for Slug Tests in Semi-Confined Aquifer Wells at Launch Complex 34

Well	Test	Method	K (ft/d)	Response
PA-20	a	Bouwer and Rice	4.1	Good
PA-20	b	Bouwer and Rice	6.9	Good
PA-20	a	Horslev	8.6	Good
PA-20	b	Horslev	29.9	Good
PA-21	a	Bouwer and Rice	0.7	Excellent
PA-21	b	Bouwer and Rice	0.8	Excellent
PA-21	a	Horslev	1.1	Excellent
PA-21	b	Horslev	1.1	Excellent
PA-22	a	Bouwer and Rice	0.4	Excellent
PA-22	b	Bouwer and Rice	0.5	Excellent
PA-22	a	Horslev	1.5	Excellent
PA-22	b	Horslev	1.1	Excellent

- Ground-water sampling in the three semi-confined aquifer wells confirmed that dissolved-phase CVOCs were present in the semi-confined aquifer at all three locations.
- At PA-20, in the parking lot north of the test plots, there was no DNAPL in any of the soil samples.
- At PA-21, in the ISCO plot, soil analysis indicated that DNAPL was present both in the Lower Clay Unit and in the Lower Sand Unit, immediately above the aquitard. No DNAPL was found in the semi-confined aquifer at this location.
- At PA-22 in the resistive heating plot, PID screening and field extraction/laboratory analysis of the soil

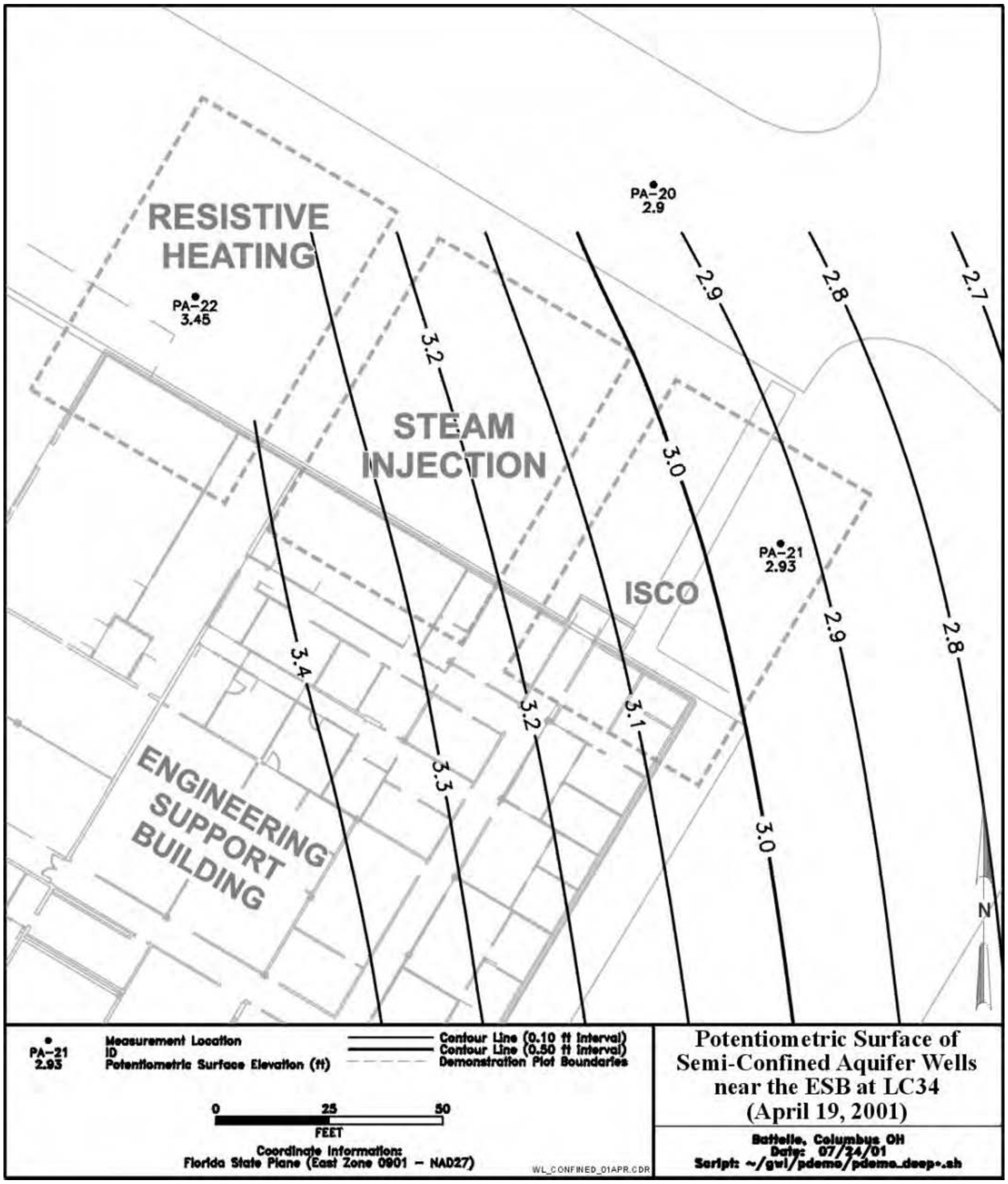


Figure 5-33. Hydraulic Gradient in the Semi-Confined Aquifer (April 19, 2001)

Table 5-21. Summary of Gradient Direction and Magnitude in the Semi-Confined Aquifer

Date	**4/19/01**	**5/24/01**	**7/2/01**	**8/28/01**	**11/8/01**	**12/4/01**	**1/21/02**	**1/25/02**	**2/20/02**
Direction	ENE ↗	E →	ENE ↗	SW ↙	NE ↗	NW ↖	ESE ↘	ESE ↘	ENE ↗
Magnitude (ft/ft)	0.0046	0.0056	0.0052	0.0033	0.0028	0.0013	0.0014	0.0013	0.0026

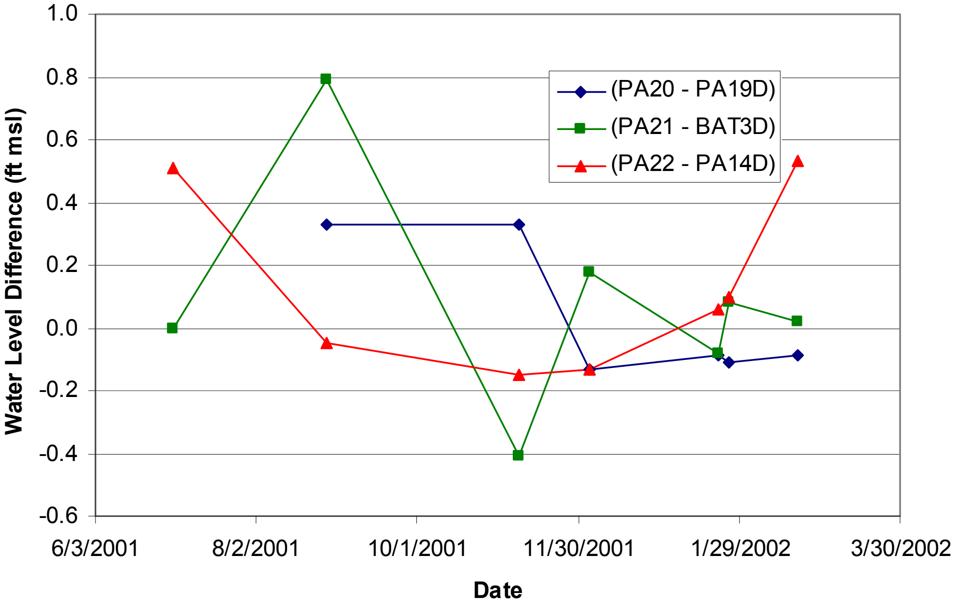


Figure 5-34. Vertical Gradients from the Spatially Neighboring Paired Wells between the Surficial Aquifer and the Semi-Confined Aquifer

samples indicated that DNAPL was present in the Lower Clay Unit and in the semi-confined aquifer, although not in the Lower Sand Unit, immediately above the aquitard. No monitoring was done in the semi-confining layer (Lower Clay Unit) or in the semi-confined aquifer before the demonstration because of NASA’s concern about breaching the relatively thin aquitard. Subsequently, these three wells were drilled because nonintrusive (seismic) monitoring indicated the possibility of DNAPL being present in the semi-confined aquifer. Because there is no information regarding the state of the semi-confined aquifer before the demonstration, it is unclear whether the DNAPL had migrated to the confined aquifer before or during the demonstration. However, given the strong electrical heating achieved in the Lower Sand Unit (in the surficial aquifer) which would tend to volatilize TCE upward, the greater probability is that the DNAPL penetrated the Lower Clay Unit before the demonstration. Whereas the Lower Clay Unit is 3 ft thick in other parts of Launch Complex 34, near PA-22 it appears to contain sand lenses that reduce the effective thickness of the aquitard to approximately 1.5 ft. Therefore, the barrier to downward migration is geologically weaker in this region.

- Hydraulic measurements in the semi-confined aquifer indicate an eastward gradient similar to the overlying surficial aquifer. Vertical gradients fluctuate between the semi-confined aquifer and the surficial aquifer.

- As the semi-confined aquifer extends down to approximately 120 ft bgs, additional investigation of the deeper geologic strata would be required to obtain an understanding of the CVOC distribution in the semi-confined aquifer.

5.3.3 Potential TCE Losses during Hot Soil Core Sampling

Even after waiting for three months following the end of resistive heating application to the subsurface, the test plot had cooled down only to 90°C or less (from a maximum of 120°C during heating). Therefore, post-demonstration soil coring had to be conducted while the plot was still hot. To minimize CVOC losses due to volatilization, the following steps were taken:

- Soil coring was started only after steam generation had subsided and the plot had cooled to 90°C or less in all parts.
- As the core barrel was retrieved from the ground, each 2-inch-diameter, 4-ft-long acetate sleeve in the core barrel was capped on both ends and dipped in an ice bath until the core soil was cooled to ambient temperature. The soil core was kept in the ice bath long enough for cooling to occur without breaking the seals at the capped ends.
- Upon reaching ambient temperature, the core sleeve was then uncapped and cut open along its length to collect the soil sample for CVOC analysis.

In order to determine volatilization losses due to the hot soil care, surrogate of 1,1,1-TCA was spiked for a few soil samples as described in Appendix G. Overall, the results show that between 84 and 113% of the surrogate spike was recovered from the soil cores. The results also indicate that the timing of the surrogate spike (i.e., pre- or post-cooling) appeared to have only a slight effect on the amount of surrogate recovered (see Table G-1 in Appendix G). Slightly less surrogate was recovered from the soil cores spiked prior to cooling, which implies that any losses of 1,1,1-TCA in the soil samples spiked prior to cooling are minimal and acceptable, within the limitations of the field sampling protocol.

5.3.4 Summary of Fate of TCE-DNAPL in the Plot

The change in TCE-DNAPL mass in the plot can be explained by the following pathways:

- *Aboveground recovery*. Vapor sampling conducted by the resistive heating vendor indicates that 1,947 kg of total TCE was recovered in the vapor extraction system. The initial estimate of total TCE mass in the subsurface was 11,313 kg.
- *Degradation by biological or abiotic processes*. There are indications that some TCE may have been degraded due to the heating in the resistive heating plot.
  - The sharp increase in *cis*-1,2-DCE levels in several monitoring wells inside the plot and perimeter indicate the possibility that some TCE may have degraded by reductive dechlorination. Microbial counts in soil and groundwater samples before and after the demonstration indicate that microbial populations survived the heat treatment in most parts of the plot. Recent research (Truex, 2003) indicates that TCE biodegradation rates are accelerated substantially at higher temperatures. Therefore, there is a strong possibility that some of the TCE in the plot has biodegraded to *cis*-1,2-DCE, but that the dechlorination is not yet complete. If TCE degradation to *cis*-1,2-DCE has been hastened, it is unclear as to the time frame over which *cis*-1,2-DCE itself may degrade. Accumulation of *cis*-1,2-DCE shows that the rate of degradation of TCE may be much faster than the rate of *cis*-1,2-DCE degradation.
  - The sharp increase in chloride, which would have been a strong indicator of dechlorination of CVOCs, proved to be inconclusive. Sodium, potassium, sulfate, alkalinity, and TDS increased sharply, concomitant with the increase in chloride—these are all seawater constituents. The possibility that the increase in chloride was caused by saltwater intrusion during the resistive heating application cannot be ruled out.
  - Abiotic processes that may have degraded TCE include reductive dechlorination by the steel shot in the electrodes, hydrolysis, and/or oxidation. Any of these processes could have been promoted by the heating in the plot.
- *Migration to surrounding regions*. It is possible that some TCE, and perhaps DNAPL, may have migrated to regions surrounding the resistive heating plot.
  - Monitoring wells (IW-17S and IW-17I) outside the western perimeter of the plot showed a sustained increase in TCE concentrations during and after the demonstration. TCE was found in transient surface water that appeared along a ditch on the western side of the plot, following the two hurricane events. It is

possible that when the water table rose to the ground surface, the vapor extraction piping in the plot was submerged. Hot water laden with TCE could have migrated westward along the topographic gradient. Another possible obstruction to the TCE vapors being extracted through the extraction pipes and plenum in the vadose zone and ground surface is the Middle Fine-Grained Unit. TCE vapors and steam migrating upwards could preferentially migrate horizontally in the sandy layer under the Middle Fine-Grained Unit rather than through the silty layer above. A limited number of exploratory soil cores collected in the regions surrounding the resistive heating plot after the demonstration did not show any signs of fresh DNAPL deposits.

- DNAPL appeared in two of the wells (PA-2I and PA-2D) on the eastern side of the plot. It is not clear which of the two technologies, ISCO or resistive heating, caused DNAPL to migrate. ISCO in the neighboring test plot (80 ft away) created strong hydraulic gradient that could potentially displace any mobile DNAPL in the aquifer. Resistive heating generates heat-induced convection gradients that could displace mobile DNAPL or mobilize residual DNAPL. On the other hand, the PA-2 well cluster was installed in a region that was showing dissolved TCE levels close to its solubility before the demonstration. It is possible that DNAPL would have eventually appeared in these wells even if there were no remediation activities at the site.

- Soil core samples from the vadose zone in the resistive heating did not show any noticeable increase in TCE concentrations.

- Surface emission tests conducted inside and around the plot on several occasions during and immediately following the resistive heating treatment showed noticeably elevated levels of TCE, compared to background levels. This indicated that the vapor capture system was not as efficient as would be desired and some CVOC vapors were migrating to the atmosphere. On some occasions, steam (and probably CVOC vapors) shot out of the monitoring wells for several seconds during sampling. This is another potential route for CVOC vapors.

- After the resistive heating and ISCO treatment demonstrations, three wells were installed into the semi-confined aquifer—one in the parking lot to the north (PA-20), one in the ISCO plot (PA-21) and one in the resistive heating plot (PA-22). All three wells showed elevated levels of dissolved TCE, but the levels were especially high in PA-22. Ground water in PA-22 also had elevated temperature (44 to 49°C). It is possible that heat conduction was responsible for elevating the temperature in the semi-confined aquifer below the resistive heating plot, although penetration of heated water from the surficial aquifer through the thin Lower Clay Unit cannot be ruled out. The soil cores collected during the installation of these wells showed the presence of DNAPL in the Lower Clay Unit and semi-confined aquifer below the ISCO plot and below the resistive heating plot, but not under the parking lot, which is outside the suspected DNAPL source zone. DNAPL concentrations were particularly high under the resistive heating plot. Because these wells were installed only after the demonstration, it is unclear as to when the DNAPL migrated to the semi-confined aquifer. The resistive heating treatment heated the base of the aquifer and probably the aquitard fairly well and the buoyancy of the water would probably create vertically upward gradients. On the other hand, the Lower Clay Unit is thinnest in the resistive heating plot (1.5 ft effective thickness versus 3 ft in other parts of Launch Complex 34). It is possible that the DNAPL penetrated the aquitard gradually over time, long before the demonstration.

- *Losses during sampling of hot soil cores*. It is possible that some CVOC losses occurred during post-demonstration sampling of the hot (90°C or less) soil cores. However, tests conducted to determine volatilization losses by spiking hot soil samples with 1,1,1-TCA surrogate indicated that any such losses were minimal. The spike test results show that between 84 and 113% of the surrogate spike was recovered from the soil cores. All precautions had been taken to minimize any such losses. By the time the post-demonstration soil sampling was done, the plot had cooled to 90°C or less, indicating that steam generation had subsided. Each time the soil sample sleeve from the barrel was retrieved from the ground, it was immediately capped at both ends of the sleeve and submerged in an ice bath until the core temperature cooled to ambient.

- In summary, the monitoring indicates that some TCE may have degraded through one or more of several heat-induced degradation mechanisms and/or that some TCE may have migrated from the resistive heating plot through a variety of possible pathways. It also is possible that some of the migrating TCE was DNAPL. The resistive heating application at Launch Complex 34 generated the desired heating in most parts of the plot, even in difficult spots, such as immediately above the aquitard and under the building. Heating in the shallower regions of the plot was somewhat hampered by the deficiencies of the new electrode design and by the transient diminishing of the vadose zone. Vapor capture and hydraulic control are the biggest challenges that the technology needs to engineer for in future applications, in order to ensure that all the mobilized or volatilized TCE-DNAPL is captured. At Launch Complex 34, a mechanism (such as a pipe) for channeling upward-migrating CVOC vapors past the Middle Fine-Grained Unit would have probably improved vapor capture. Better hydraulic and pneumatic control, as well as better heating, near the water table, vadose zone, and ground surface would have reduced TCE-DNAPL migration potential.

In summary, the TCE in the plot probably was dissipated by the resistive heating treatment through a number of possible pathways, including aboveground vapor recovery and condensation, microbial degradation, and migration to the surrounding regions. The possible buildup and persistence of *cis*-1,2-DCE in the plot, as well as dechlorination to ethenes, due to heat-accelerated biodegradation needs to be studied. Ways of maximizing any such biodegradation and minimizing migration outside the plot need to be determined during future resistive heating applications.

5.4 Operating Requirements and Cost

Section 3 contains a description of the resistive heating treatment field operations at Launch Complex 34. Section 7 contains the costs and economic analysis of the technology.

6. Quality Assurance

A QAPP (Battelle, 1999d) prepared before the demonstration outlined the performance assessment methodology and the QA measures to be taken during the demonstration. The results of the field and laboratory QA for the critical soil and ground-water CVOC (primary) measurements and ground-water field parameter (secondary) measurements are described in this section. The results of the QA associated with other ground-water quality (secondary) measurements are described in Appendix G. The focus of the QA is on the critical TCE measurement in soil and ground water, for which, in some cases, special sampling and analytical methods were used. For other measurements (chloride, calcium, etc.), standard sampling and analytical methods were used to ensure data quality.

6.1 QA Measures

This section describes the data quality in terms of representativeness and completeness of the sampling and analysis conducted for technology performance assessment. Chain-of-custody procedures also are described.

6.1.1 Representativeness

Representativeness is a measure that evaluates how closely the sampling and analysis represents the true value of the measured parameters in the target matrices. The critical parameter in this demonstration is TCE concentration in soil. The following steps were taken to achieve representativeness of the soil samples:

- Statistical design for determining the number and distribution of soil samples in the 75-ft × 50-ft resistive heating plot, based on the horizontal and vertical variability observed during a preliminary characterization event (see Section 4.1). Twelve locations (one in each cell of a 4 x 3 grid in the plot) were cored before and after the demonstration and a continuous core was collected and sampled in 2-ft sections from ground surface to aquitard at each coring location. At the 80% confidence level, the pre- and post-demonstration TCE mass estimates in the plot (see Section 5.1) were within relatively narrow intervals that enabled a good judgment of the mass removal achieved by the resistive heating technology.
    - o Sampling and analysis of duplicate post-demonstration soil cores to determine TCE concentration variability within each grid cell. Two complete cores (SB-204 and SB-304) were collected within about 2 ft of each other in the post-demonstration resistive heating plot, with soil sampling at every 2-ft interval (see Figure 5-1 for the TCE analysis of these cores). The resulting TCE concentrations showed a relatively good match between the duplicate cores. This indicated that dividing the resistive heating plot into 12 grid cells enabled a sampling design that was able to address the horizontal variability in TCE distribution.
    - o Continuous sampling of the soil column at each coring location enabled the sampling design to address the vertical variability in the TCE distribution. By extracting and analyzing the complete 2-ft depth in each sampled interval, essentially every vertical depth was sampled.
- Use of appropriate modifications to the standard methods for sampling and analysis of soil. To increase the representativeness of the soil sampling, the sampling and extraction procedures in EPA Method 5035 were modified so that an entire vertical section of each 2-ft core could be sampled and extracted, instead of the 5-g aliquots specified in the standard method (see Section 4.1). This was done to maximize the capture of TCE-DNAPL in the entire soil column at each coring location.

Steps taken to achieve representativeness of the ground-water samples included:

- Installation and sampling of two well clusters in the 75-ft × 50-ft resistive heating plot. Each cluster consisted of three wells screened in the three stratigraphic units—Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit.

- Use of standard methods for sampling and analysis. Disposable tubing was used to collect samples from all monitoring wells to avoid persistence of TCE in the sample tubing after sampling wells with high TCE (DNAPL) levels.

6.1.2 Completeness

All the regular samples planned in the QAPP were collected and analyzed, plus additional samples were collected when new requirements were identified as the demonstration progressed. Additional ground-water samples were collected from all resistive heating plot and surrounding wells to better evaluate the generation and migration of chloride, and the presence of potassium ion and potassium permanganate from the ISCO demonstration. One additional soil core was collected during post-demonstration sampling to evaluate the variability within the same grid cell.

All the quality control (QC) samples planned in the QAPP were collected and analyzed, except for the equipment rinsate blanks during soil coring. Equipment rinsate blanks were not planned in the draft QAPP and were not collected during the pre-demonstration soil coring event. These blanks were later added to the QAPP and were prepared during the post-demonstration soil coring event. Based on the preliminary speed of the soil coring, one rinsate blank per day was thought to be sufficient to obtain a ratio of 1 blank per 20 samples (5%). However, as the speed of the soil coring increased, this frequency was found to have fallen slightly short of this ratio. The same rinsing procedure was maintained for the soil core barrel through the pre- and post-demonstration sampling. None of the blanks contained any elevated levels of CVOCs.

6.1.3 Chain of Custody

Chain-of-custody forms were used to track each batch of samples collected in the field and were delivered either to the on-site mobile laboratory or to the off-site analytical laboratory. Copies of the chain-of-custody records can be found in Appendix G. Chain-of-custody seals were affixed to each shipment of samples to ensure that only laboratory personnel accessed the samples while in transit. Upon arrival at the laboratory, the laboratory verified that the samples were received in good condition and the temperature blank sample sent with each shipment was measured to ensure that the required temperature was maintained during transit. Each sample received was then checked against the chain-of-custody form, and any discrepancies were brought to the attention of field personnel.

6.2 Field QC Measures

The field QC checks included calibration of field instruments, field blanks (5% of regular samples), field duplicates (5% of regular samples), and trip blanks; the results of these checks are discussed in this section.

Table 6-1 summarizes the instruments used for field ground-water measurements (pH, ORP, DO, temperature, water levels, and conductivity) and the associated calibration criteria. Instruments were calibrated at the beginning and end of the sampling period on each day. The field instruments were always within the acceptance criteria during the demonstration. The DO membrane was the most sensitive, especially to extremely high (near saturation) levels of chlorinated solvent or permanganate in the ground water and this membrane had to be changed more frequently. Because of interference with DO and other measurements, field parameter measurements in deeply purple (high permanganate level) samples were avoided, as noted in Appendix G.

6.2.1 Field QC for Soil Sampling

Soil extractions were conducted in the field and the extract was sent to the off-site laboratory for CVOC analysis. A surrogate compound was initially selected to be spiked directly into a fraction of the soil samples collected, but the field surrogate addition was discontinued at the request of the off-site laboratory because of interference and overload of analytical instruments at the

Table 6-1. Instruments and Calibration Acceptance Criteria Used for Field Measurements

Instrument	Measurement	Acceptance Criteria
YSI Meter Model 6820	pH	3 point, ±20% difference
YSI Meter Model 6820	ORP	1 point, ±20% difference
YSI Meter Model 6820	Conductivity	1 point, ±20% difference
YSI Meter Model 6820	Dissolved Oxygen	1 point, ±20% difference
YSI Meter Model 6820	Temperature	1 point, ±20% difference
Ohaus Weight Balance	Soil – Dry/Wet Weight	3 point, ±20% difference
Hermit Water-Level Indicator	Water Levels	±0.01 ft

detection limits required. Surrogate addition was instead conducted by the analytical laboratory, which injected the surrogate compound into 5% of the methanol extracts prepared in the field. As an overall determination of the extraction and analytical efficiency of the soil sampling, the modified EPA Method 5035 methanol extraction procedure was evaluated before the demonstration by spiking a known amount of TCE into soil samples from the Launch Complex 34 aquifer. A more detailed evaluation of the soil extraction efficiency was conducted in the field by spiking a surrogate compound (1,1,1-TCA) directly into the intact soil cores retrieved in a sleeve. The injection volume of 1,1,1-TCA was approximately 10 µL. The spiked soil samples were handled in the same manner as the remaining soil samples during the extraction procedure. Of the 13 soil samples spiked with 1,1,1-TCA, 12 were within the acceptable range of precision for the post-demonstration soil sampling, calculated as the relative percent difference (RPD), where RPD is less than 30%. The results indicate that the methanol extraction procedure used in the field was suitable for recovering CVOCs. Extraction efficiencies ranged from 84 to 113% (92% average) (Tables G-1 and G-2 in Appendix G). For this evaluation, soil samples from the pre-demonstration soil core PA-4 were homogenized and spiked with pure TCE. Replicate samples from the spiked soil were extracted and analyzed; the results are listed in Appendix G (Table G-3). For the five replicate soil samples, the TCE spike recoveries were in the range of 72 to 86%, which fell within the acceptable range (70-130%) for QA of the extraction and analysis procedure.

Duplicate soil samples were collected in the field and analyzed for TCE to evaluate sampling precision. Duplicate soil samples were collected by splitting each 2-ft soil core vertically in half and subsequently collecting approximately 250 g of soil into two separate containers, marked as SB#-Depth#-A and B. Appendix G (Table G-4) shows the result of the field soil duplicate analysis and the precision, calculated as the RPD for the duplicate soil cores, which were collected before and after the demonstration. The precision of the field duplicate samples was generally within the acceptable range (±30%) for the demonstration, indicating that the sampling procedure was representative of the soil column at the coring location. The RPD for three of the duplicate soil samples from the pre-demonstration sampling was greater than 30%, but less than 60%. This indicated that the repeatability of some of the pre-demonstration soil samples was outside targeted acceptance criteria, but within a reasonable range, given the heterogeneous nature of the contaminant distribution. The RPDs for six of the duplicate soil samples from the post-demonstration sampling were greater than 30%; five of the six samples had an RPD above 60%. This indicates that the ISCO treatment created greater variability in the contaminant distribution. Part of the reason for the higher RPD calculated in some post-demonstration soil samples is that TCE concentrations tended to be low (often near or below the detection limit). For example, the RPD between duplicate samples, one of which is below detection and the other slightly above detection, tends to be high. In general, though, the variability in the two vertical halves of each 2-ft core was in a reasonable range, given the typically heterogeneous nature of the DNAPL distribution.

Field blanks for the soil sampling consisted of rinsate blank samples and methanol blank samples. The rinsate blank samples were collected once per drilling borehole (approximately 20 soil samples) to evaluate the decontamination efficiency of the sample barrel used for each soil boring. Decontamination between samples consisted of a three-step process where the core barrel was emptied, washed with soapy water, rinsed in distilled water to remove soap and debris, and then rinsed a second time with distilled water. The rinsate blank samples were collected by pouring distilled water through the sample barrel, after the barrel had been processed through the routine decontamination procedure. As seen in Appendix G (Table G-5), TCE levels in the rinsate blanks were always below detection (<5.0 µg/L), indicating that the decontamination procedure was helping control carry-over of CVOCs between samples.

Methanol method blank samples (5%) were collected in the field to evaluate the soil extraction process. The results are listed in Appendix G (Table G-6). These samples were generally below the targeted detection limit of 1 mg/kg of TCE in dry soil. Detectable levels of TCE were present in methanol blanks sampled on June 23, 1999 (1.8 mg/kg), June 29, 1999 (8.0 mg/kg), and July 16, 1999 (1.2 mg/kg) during the pre-demonstration phase of the project, but were still relatively low. The slightly elevated levels may be due to the fact that many of the soil samples extracted on these days were from high-DNAPL regions and contained extremely high TCE concentrations. The TCE concentrations in these blanks were below 10% of the concentrations in the associated batch of soil samples. All the post-demonstration methanol blanks were below detection.

6.2.2 Field QC Checks for Ground-Water Sampling

QC checks for ground-water sampling included field duplicates (5%), field blanks (5%), and trip blanks. Field duplicate samples were collected once every 20 wells sampled. Appendix G (Tables G-7 and G-8) contains the analysis of the field duplicate ground-water samples that were collected before, during, and after the demonstration. The RPD (precision) calculated for these samples always met the QA/QC target criteria of ±30%.

Decontamination of the sample tubing between ground-water samples initially consisted of a detergent rinse and two distilled water rinses. However, initial ground-water sampling results revealed that, despite the most thorough decontamination, rinsate blanks contained elevated levels of TCE, especially following the sampling of wells containing TCE levels near or greater than its solubility (1,100 mg/L); this indicated that some free-phase solvent may have been drawn into the tubing. When TCE levels in such rinsate blanks refused to go down, even when a methanol rinse was added to the decontamination procedure, a decision was made to switch to disposable Teflon® tubing. Each new piece of tubing was used only for sampling each well once and then discarded, despite the associated costs. Once disposable sample tubing was used, TCE levels in the rinsate blanks (Appendix G, Tables G-9 and G-10) were below the targeted detection limit (3.0 µg/L) throughout the demonstration. The only exception was one rinsate blank collected during the post-demonstration sampling event on May 20, 2000; this rinsate blank contained 11 µg/L of TCE, which was less than 10% of the TCE concentrations in the regular samples in this batch.

TCE levels in trip blank samples were always below 5 µg/L (Appendix G, Table G-11), indicating the integrity of the samples was maintained during shipment. In some batches of ground-water samples, especially when excess permanganate was present in the sample, detection limits were raised from 3 to 5 µg/L to avoid instrument interference.

6.3 Laboratory QC Checks

The on-site mobile and off-site analytical laboratories performed QA/QC checks consisting of 5% matrix spikes (MS) or laboratory control spikes (LCS), as well as the same number of matrix spike duplicates (MSD) or laboratory control spike duplicates (LCSD). The analytical laboratories generally conducted MS and MSD whenever the ground-water samples were clear, in order to determine accuracy. However, when excess permanganate was present in the samples, as with many post-demonstration samplers, LCS and LCSD were conducted. MS and MSD or LCS and LCSD were used to calculate analytical accuracy (percent recovery) and precision (RPD between MS and MSD or LCS and LCSD).

6.3.1 Analytical QC Checks for Soil

Analytical accuracy for the soil samples (methanol extracts) analyzed were generally within acceptance limits (70-130%) for the pre-demonstration period (Appendix G, Table G-12). The batch of regular samples on August 22, 1999 had very high levels of TCE (near saturation), which tended to mask the spiked TCE. Matrix spike recoveries were outside this range for three of the MS/MSD samples conducted during the post-demonstration sampling period (Appendix G, Table G-13), but still within 50 to 150%; this indicates that although there may have been some matrix effects, the recoveries were still within a reasonable range, given the matrix interference. Matrix spike recovery was 208% for one of the matrix spike repetitions on June 1, 2000. The precision between MS and MSD was always within acceptance limits (±25%). Laboratory control spike recoveries and precision were within the acceptance criteria (Appendix G, Tables G-14 and G-15).

The laboratories conducted surrogate spikes in 5% of the total number of methanol extracts prepared from the soil samples for CVOC analysis. Table 6-2 lists the surrogate and matrix spike compounds used by the on-site laboratory to perform the QA/QC checks. Table 6-3 lists the surrogate and matrix spike compounds used by the off-site laboratory to perform the QA/QC checks. Surrogate and matrix spike recoveries were always within the specified acceptance limits. Method blank samples were run at a frequency of at least one for every 20 samples analyzed in the pre- and post-demonstration periods

Table 6-2. List of Surrogate and Matrix Spike Compounds and Their Target Recoveries for Ground-Water Analysis by the On-Site Laboratory

Surrogate Compound DHL	Matrix Spike Compound DHL
a,a,a-Trifluorotoluene (75-125%)	*cis*-1,2-DCE (70-130%) *trans*-1,2-DCE (70-130%) Vinyl chloride (65-135%) TCE (70-130%)

Table 6-3. Surrogate and Laboratory Control Sample Compounds and Their Target Recoveries for Soil and Ground-Water Analysis by the Off-Site Laboratory

Surrogate Compound STL	Matrix Spike Compound STL
Dibromofluoromethane (66-137%) 1,2-Dichloroethane – d4 (61-138%) Toluene – d8 (69-132%) Bromofluorobenzene (59-145%)	Vinyl chloride (56-123%) Carbon tetrachloride (60-136%) Benzene (70-122%) 1,2-Dichloroethane (58-138%) TCE (70-130%) 1,2-Dichloropropane (68-125%) 1-1,2-Trichloroethane (63-123%) Tetrachloroethane (70-125%) 1,2-Dibromoethane (66-126%) Bromoform (60-131%) 1,4-Dichlorobenzene (70-120%) *cis*-1,3-Dichloropropane (65-132%)

(Appendix G, Tables G-16 and G-17). CVOC levels in the method blanks were always below detection.

6.3.2 Laboratory QC for Ground Water

Pre- and post-demonstration MS and MSD results for ground water are listed in Appendix G (Table G-18). The MS and MSD recoveries (70 to 130%) and their precision (±25%) were generally within acceptance criteria. The only exceptions were the samples collected on August 3, 1999 and January 14, 2000 during the ongoing demonstration phase which had MS and MSD recoveries that were outside the range due to high initial TCE concentrations in the samples. Recoveries and RPDs for LCS and LCSD samples (Appendix G, Tables G-19 and G-20) were always within the acceptance range.

Method blanks (Appendix G, Tables G-21 and G-22) for the ground-water samples were always below the targeted 3-µg/L detection limit.

6.3.3 Analytical Detection Limits

Detection limits for TCE in soil (1 mg/kg) and ground water (3 µg/L) generally were met. The only exceptions were samples that had to be diluted for analysis, either because one of the CVOC compounds (e.g., TCE) was at a relatively high concentration as compared to another VOC compound (e.g., *cis*-1,2-DCE) or because excessively high levels of organics in the sample necessitated dilution to protect instruments. The proportionately higher detection limits are reported in the CVOC tables in Appendix C. The detection limits most affected were the ones for *cis*-1,2-DCE and vinyl chloride, due to the masking effect of high levels of TCE. Additionally, the laboratories verified and reported that analytical instrumentation calibrations were within acceptable range on the days of the analysis.

6.4 QA/QC Summary

Given the challenges posed by the typically heterogeneous TCE distribution in a DNAPL source zone, the collected data were a relatively good representation of the TCE distribution in the Launch Complex 34 aquifer before, during, and after the demonstration, for the following reasons:

- Sufficient number of locations (12) were sampled within the plot to adequately capture the horizontal variability in the TCE distribution. The continuous sampling of the soil at each coring location ensured that the vertical variability of the TCE distribution was captured. Sampling and analytical procedures were appropriately modified to address the expected variability. At the 80% confidence level, the soil sampling provided pre- and post-demonstration confidence intervals (range of TCE mass estimates) that were narrow enough to enable a good judgment of the TCE and DNAPL mass removal achieved by the resistive heating technology.
- Standard sampling and analysis methods were used for all other measurements to ensure that data were comparable between sampling events.
- Accuracy and precision of the soil and ground-water measurements were generally in the acceptable range for the field sampling and laboratory analysis. In the few instances that QC data were outside the targeted range, extremely low (near detection) or extremely high levels of TCE in the sample caused higher deviation in the precision (repeatability) of the data.
- The masking effect of high-TCE levels on other CVOCs and the need for sample dilution caused detection limits for TCE, in some cases, to rise to 5 µg/L (instead of 3 µg/L). However, post-demonstration levels of dissolved TCE in many of the monitoring wells in the resistive heating plot were considerably higher than the 3-µg/L detection and regulatory target.
- Field blanks associated with the soil samples generally had acceptably low or undetected levels of TCE. After suitable modifications to account for the persistence of DNAPL in ground-water sampling tubing, TCE levels in field blanks were acceptably low or below detection.

7. Economic Analysis

The cost estimation for the resistive heating technology application involves the following three major components:

- Application cost of resistive heating at the demonstration site. Costs of the technology application at Launch Complex 34 were tracked by the resistive heating vendor and by MSE, the DOE contractor who subcontracted the vendor.
- Site preparation and waste disposal costs incurred by the owner. NASA and MSE tracked the costs incurred by the site owner.
- Site characterization and performance assessment costs. Battelle and TetraTech EM, Inc., estimated these costs based on the site characterization and performance assessment that was generally based on U.S. EPA's SITE Program guidelines.

An economic analysis for an innovative technology generally is based on a comparison of the cost of the innovative technology with a conventional alternative. In this section, the economic analysis involves a comparison of the resistive heating cost with the cost of a conventional pump-and-treat system.

7.1 Resistive Heating Treatment Costs

Table 7-1. Resistive Heating Application Cost Summary Provided by Vendor

Cost Item	Actual Cost ($)	Percentage (%)
Design and submittals	45,808	8.0
Mobilization of equipment	63,230	11.0
Temporary utilities setup	7,007	1.2
Air, water, and limited soil analyses	17,806	3.1
Condensate collection and storage	5,175	1.0
Gas/vapor collection system	38,952	6.8
Waste containment	4,620	0.8
Transport/disposal of drill cuttings	39,713	7.0
Resistive heating operations	196,194	34.5
Electricity used	72,484	12.8
Site restoration	5,380	1.0
Demobilization of equipment	58,837	10.3
Final report	13,536	2.5
Total Cost	**568,742**	**100**

Source: CES, 2001.

The costs of the resistive heating treatment technology were tracked and reported by both the vendor and MSE, the DOE contractor who subcontracted the vendor. Table 7-1 summarizes the cost breakdown for the treatment. The total cost of the resistive heating demonstration incurred by the vendor was approximately $569,000. This total includes the design, permitting support, implementation, process monitoring, and reporting costs incurred by the vendor. The total does not include the costs of site characterization, which was conducted by other organizations (Remedial Investigation/Feasibility Study [RI/FS] by NASA, preliminary characterization by WSRC, detailed characterization by Battelle/TetraTech EM, Inc./U.S. EPA) and the cost of the operating waste disposal (incurred by NASA).

MSE separately estimated the unit treatment cost for the resistive heating treatment demonstration to be approximately \$29/lb of TCE removed, which translates to the treatment cost of approximately \$104/yd^3 (MSE, 2002). The estimated unit cost takes consideration of the treated/removed TCE in the plot, not accounting for the remainder of total TCE present in the resistive heating plot.

7.2 Site Preparation and Waste Disposal Costs

Soil cuttings from the hollow-stem auger used for installing the resistive heating electrodes were disposed of off site by the vendor and the costs are shown in Table 7-1. The wastes generated during resistive heating operation were disposed of off site by NASA at a cost of $44,000.

Wastes shipped off site included the spent GAC (sent to Arizona for regeneration), permanganate-impregnated silica (shipped to a nearby landfill), and steam condensate (transported to the on-site wastewater treatment facility).

7.3 Site Characterization and Performance Assessment Costs

This section describes two categories of costs:

- Site characterization costs. These are the costs that a site would incur in an effort to bridge the gap between the general site information in an RI/FS or RFI report and the more detailed information required for DNAPL source delineation and remediation technology design. This cost component is perhaps the most reflective of the type of costs incurred when a site of the size and geology of Launch Complex 34 undergoes site characterization in preparation for remediation. Presuming that ground-water monitoring and plume delineation at a site indicates the presence of DNAPL, these site characterization costs are incurred in an effort to define the boundaries of the DNAPL source zone, obtain an order-of-magnitude estimate of the DNAPL mass present, and define the local hydrogeology and geochemistry of the DNAPL source zone.
- Performance assessment costs. These are primarily demonstration-related costs. Most of these costs were incurred in an effort to further delineate the portion of the DNAPL source contained in the resistive heating plot and determine the TCE-DNAPL mass removal achieved by resistive heating. Only a fraction of these costs would be incurred during full-scale deployment of this technology; depending on the site-specific regulatory requirements, only the costs related to determining compliance with cleanup criteria would be incurred in a full-scale deployment.

Table 7-2 summarizes the costs incurred by Battelle for the February 1999 site characterization. The February 1999 site characterization event was a suitable combination of soil coring and ground-water sampling, organic and inorganic analysis, and hydraulic testing (water levels and slug tests) that may be expected to bridge the gap between the RI/FS or RFI data usually available at a site and the typical data needs for DNAPL source delineation and remediation design.

Performance assessment costs incurred jointly by Battelle and TetraTech EM, Inc., are listed in Table 7-3.

Table 7-2. Estimated Site Characterization Costs

Activity	Cost
Site Characterization Work Plan • Additional characterization to delineate DNAPL source • Collect hydrogeologic and geochemical data for technology design	$ 25,000
Site Characterization • Drilling – soil coring and well installation (12 continuous soil cores to 45 ft bgs; installation of 36 monitoring wells) • Soil and ground-water sampling (36 monitoring wells; 300 soil samples collection and field extraction) • Laboratory analysis (organic and inorganic analysis) • Field Measurements (water quality; hydraulic testing)	$ 165,000
Data Analysis and Site Characterization Report	$ 65,000
Total	**$ 255,000**

Table 7-3. Estimated Performance Assessment Costs

Activity	Cost
Pre-Demonstration Assessment • Drilling – 12 continuous soil cores, installation of 18 monitoring wells • Soil and ground-water sampling for TCE-DNAPL boundary and mass estimation (36 monitoring wells; 300 soil samples collection and field extraction) • Laboratory analysis (organic and inorganic analysis) • Field measurements (water quality; hydraulic testing)	$208,000
Demonstration Assessment • Ground-water sampling (ISCO plot and perimeter wells) • Laboratory analysis (organic and inorganic analysis) • Field measurements (water quality; hydraulic testing; ISCO plot and perimeter wells)	$240,000
Post-Demonstration Assessment • Drilling – 12 continuous soil cores • Soil and ground-water sampling (36 monitoring wells; collection and field extraction of 300 soil samples) • Laboratory analysis (organic and inorganic analysis) • Field measurements (water quality; hydraulic testing)	$215,000
Total	**$ 663,000**

7.4 Present Value Analysis of Resistive Heating and Pump-and-Treat System Costs

DNAPL, especially of the magnitude present at Launch Complex 34, is likely to persist in the aquifer for several decades or centuries. The resulting ground-water contamination and plume also will persist for several decades. The conventional approach to this type of contamination has been the use of pump-and-treat systems that extract and treat the ground water above ground. This conventional technology is basically a plume control technology and would have to be implemented as long as ground-water contamination exists. Resistive heating technology is an innovative in situ technology that may be comparable to the conventional pump-and-treat approach. The economic analysis therefore compares the costs of these two alternatives.

Because a pump-and-treat system would have to be operated for the next several decades, the life-cycle cost of this long-term treatment has to be calculated and compared with the cost of the resistive heating technology, a short-term treatment. The present value (PV) of a long-term pump-and-treat application is calculated as described in Appendix H. The PV analysis is conducted over a 30-year period, as is typical for long-term remediation programs at Superfund sites. Site characterization and performance (compliance) assessment costs are assumed to be the same for both alternatives and are not included in this analysis.

For the purpose of comparison, it is assumed that a pump-and-treat system would have to treat the plume emanating from a DNAPL source the size of the resistive heating plot. Recent research (Pankow and Cherry, 1996) indicates that the most efficient pump-and-treat system for source containment would capture all the ground water flowing through the DNAPL source region. For a 75-ft-long × 50-ft-wide × 40-ft-deep DNAPL source region at Launch Complex 34, a single extraction well pumping at 2 gallons per minute (gpm) is assumed to be sufficient to contain the source in an aquifer where the hydraulic gradient (and therefore, the ground-water flow velocity) is extremely low. This type of minimal containment pumping ensures that the source is contained without having to extract and treat ground water from cleaner surrounding regions, as would be the case in more aggressive conventional pump-and-treat systems. The extracted ground water is treated with an air stripper, polishing carbon (liquid phase), and a catalytic oxidation unit (for air effluent).

As shown in Appendix H, the total capital investment for an equivalent pump-and-treat system would be approximately $167,000, and would be followed by an annual operation and maintenance (O&M) cost of $57,000 (including quarterly monitoring). Periodic maintenance requirements (replacements of pumps, etc.) would raise the O&M cost every five years to $70,000 and every 10 years to $99,000. A discount rate (real rate of return) of 2.9%, based on the current recommendation for government projects, was used to calculate the PV. The PV of the pump-and-treat costs over 30 years is estimated to be **$1,406,000**.

An equivalent treatment cost for full-scale deployment of the resistive heating technology would be approximately $613,000. This estimate is based on a total resistive heating treatment ($569,000) and waste disposal cost ($44,000) during the demonstration (from Table 7-1 and Section 7-2). Therefore, if the TCE remaining in the resistive heating plot was allowed to attenuate naturally, the total treatment cost with the resistive heating technology would be around **$613,000**. One assumption here is that the full-scale deployment of the resistive heating treatment system would entail design, equipment, and deployment similar to the kind done during the demonstration. If additional equipment or labor is required to install and operate additional/modified vapor capture and/or hydraulic control devices, there may be additional costs involved. Vapor capture and hydraulic control were the two main limitations identified during the demonstration that may require improvements at future implementation sites.

The economics of the resistive heating treatment technology compare favorably with the economics of an equivalent pump-and-treat system. As seen in Table H-3 in Appendix H, an investment in resistive heating would be recovered in the ninth year, when the PV of the pump-and-treat system exceeds the cost of resistive heating. In addition to a lower PV or life-cycle cost, there may be other tangible and intangible economic benefits to using a source remediation technology that are not factored into the analysis. For example, the economic analysis in Appendix H assumes that the pump-and-treat system is operational all the time over the next 30 years or more, with most of the annual expense associated with operation and routine (scheduled) maintenance. Experience with pump-and-treat systems at several sites has shown that downtime associated with pump-and-treat systems is fairly high (as much as 50% downtime reported from some sites). This may negatively impact both maintenance requirements (tangible cost) and the integrity of plume containment (intangible cost) with the pump-and-treat alternative.

Another factor to consider is that although the economic analysis for long-term remediation programs typically is conducted for a 30-year period, the DNAPL source and therefore the pump-and-treat requirement may persist for many more years or decades. This would lead to concomitantly higher remediation costs for the pump-and-treat or plume containment option (without source removal). As seen in Appendix H, the PV of a pump-and-treat system operated for 100 years would be $2,188,000. Even if the limitations on the effectiveness of a source removal technology at some sites necessitate the use of pump-and-treat for the next few years, until the source (and plume) is further depleted, the size of the pump-and-treat system and the time period over which it needs to be operated is likely to be considerably reduced.

8. Technology Applications Analysis

This section evaluates the general applicability of the resistive heating treatment technology to sites with contaminated ground water and soil. The analysis is based on the results and lessons learned from the IDC demonstration, as well as general information available about the technology and its application at other sites.

8.1 Objectives

This section evaluates the resistive heating technology against the nine evaluation criteria used for detailed analysis of remedial alternatives in feasibility studies under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Much of the discussion in this section applies to DNAPL source removal in general, and resistive heating in particular.

8.1.1 Overall Protection of Human Health and the Environment

Resistive heating is protective of human health and environment in both the short and long term. At Launch Complex 34 for example, resistive heating removed more than 10,000 kg of DNAPL contamination from the resistive heating plot, with the possibility of some TCE mass destruction. Because DNAPL acts as a secondary source that can contaminate an aquifer for decades or centuries, DNAPL source removal or mitigation considerably reduces the duration over which the source is active. Even if DNAPL mass removal is not 100%, the resulting long-term weakening of the plume and the reduced duration over which the DNAPL source contributes to the plume reduces the threat to potential receptors. Vapor extraction and hydraulic control need to be improved to mitigate the potential for TCE-DNAPL migration to the regions surrounding the resistive heating treatment zone.

8.1.2 Compliance with ARARs

This section describes the technology performance versus applicable or relevant and appropriate requirements (ARARs). Compliance with chemical-, location-, and action-specific ARARs should be determined on a site-specific basis.

Compliance with chemical-specific ARARs depends on the efficiency of the resistive heating process at the site and the cleanup goals agreed on by various stakeholders. In general, reasonable **short-term** (DNAPL mass removal) goals are more achievable and should lead to eventual and earlier compliance with long-term ground-water cleanup goals. Achieving **intermediate-term** ground-water cleanup goals (e.g., federal or state maximum contaminant levels [MCLs]), especially in the DNAPL source zone, is more difficult because various studies (Pankow and Cherry, 1996) have shown that almost 100% DNAPL mass removal may be required before a significant change in ground-water concentrations is observed. However, removal of DNAPL, even if most of the removal takes place from the more accessible pores, would probably result in a weakened plume that may lead to significant risk reduction in the downgradient aquifer. In the **long term**, source treatment should lead to earlier compliance with ground-water cleanup goals at the compliance boundary and earlier dismantling of any interim remedies (e.g., pump-and-treat).

The specific federal environmental regulations that are potentially impacted by remediation of a DNAPL source with resistive heating are described below.

8.1.2.1 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

CERCLA, as amended by the Superfund Amendments and Reauthorization Act (SARA), provides for federal authority to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or the environment. Remedial alternatives that significantly reduce the volume, toxicity, or mobility of hazardous materials and that provide long-term protection are preferred. Selected remedies must also be cost-effective and protective of human health and the environment. The resistive heating technology meets several of these criteria relating to a preferred alternative. Resistive heating reduces the volume of contaminants by removing DNAPL from the aquifer; it is possible that the toxicity of contaminants is reduced depending on how much the degradation pathways contribute to contaminant mass removal (see Sections 5.3.1 and 5.3.2). For example, at Launch Complex 34, as described in Section 5.3.1, there was a large increase in chloride in the ground water; some part of the chloride may have been generated by TCE degradation by microbial or abiotic mechanisms. This removal of solvent leads to a considerable reduction in the time it takes for the DNAPL source to fully deplete. Although aquifer heterogeneities and technology limitations often result in less than 100% removal of the contaminant and elevated levels of dissolved solvent may persist in the ground water over the short term, in the long term, there is faster eventual elimination of ground-water contamination. Section 7.4 shows that resistive heating is cost-effective compared with the conventional alternative of long-term pump and treat.

8.1.2.2 Resource Conservation and Recovery Act (RCRA)

RCRA, as amended by the Hazardous and Solid Waste Amendments (HSWA) of 1984, regulates management and disposal of municipal and industrial solid wastes. The U.S. EPA and RCRA-authorized states (listed in 40 CFR Part 272) implement and enforce RCRA and state regulations. Generally, RCRA does not apply to in situ ground-water treatment because the contaminated ground water may not be considered hazardous waste while it is still in the aquifer. The contaminated ground water becomes regulated if it is extracted from the ground, as would happen with the conventional alternative of pump and treat. Some aboveground wastes are generated that may require off-site landfill disposal. During the Launch Complex 34 demonstration, soil cuttings (from drilling and installation of resistive heating electrodes) and the permanganate-impregnated silica were shipped to a landfill. The spent GAC was shipped back to the supplier for regeneration.

8.1.2.3 Clean Water Act (CWA)

The CWA is designed to restore and maintain the chemical, physical, and biological quality of navigable surface waters by establishing federal, state, and local discharge standards. When steam or ground-water extraction is conducted, and the resulting water stream needs to be treated and discharged to a surface water body or a publicly owned treatment works (POTW), the CWA may apply. On-site discharges to a surface water body must meet National Pollutant Discharge Elimination System (NPDES) requirements, but may not require an NPDES permit. Off-site discharges to a surface water body must meet NPDES limits and require an NPDES permit. Discharge to a POTW, even if it is through an on-site sewer, is considered an off-site activity. At Launch Complex 34, no surface water discharge was involved at the demonstration site. Approximately 98,038 gal of condensate was generated during the demonstration. The condensate was run through a liquid-phase GAC, stored, analyzed, and transported to the on-site wastewater treatment plant.

Sometimes, soil or ground-water monitoring may lead to small amounts of purge and decontamination water wastes that may be subject to CWA requirements. Micropurging was one measure implemented at Launch Complex 34 to minimize such wastes during site characterization and technology performance assessment.

8.1.2.4 Safe Drinking Water Act (SDWA)

The SDWA, as amended in 1986, requires U.S. EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorizes national drinking water standards and a joint federal-state system for ensuring compliance with these standards. The SDWA also regulates underground injection of fluids and includes sole-source aquifer and wellhead protection programs.

The National Primary Drinking Water Standards are found at 40 CFR Parts 141 through 149. The health-based SDWA primary standards (e.g., for TCE) are more critical to meet; SDWA secondary standards (e.g., for dissolved manganese) are based on other factors, such as aesthetics (discoloration) or odor. The MCLs based on these standards generally apply as cleanup standards for water that is, or potentially could be, used for drinking water supply. In some cases, such as when multiple contaminants are present, alternative concentration limits (ACL) may be used. CERCLA and RCRA standards and guidance are used in establishing ACLs. In addition, some states may set more stringent standards for specific contaminants. For example, the federally mandated MCL for vinyl chloride is 2 µg/L, whereas the State of Florida drinking water standard is 1 µg/L. In such instances, the more stringent standard usually becomes the cleanup goal.

Although the long-term goal of DNAPL source zone treatment is meeting applicable drinking water standards or other risk-based ground-water cleanup goals agreed on between site owners and regulatory authorities, the short-term objective of resistive heating and source remediation is DNAPL mass removal. Because technology, site, and economic limitations may limit DNAPL mass removal to less than 100%, it may not always be possible to meet ground-water cleanup targets in the source region in the short term. Depending on other factors, such as the distance of the compliance point (e.g., property boundary, at which ground-water cleanup targets have to be met) from the source (as negotiated between the site owner and regulators), the degree of weakening of the plume due to DNAPL source treatment, and the degree of natural attenuation in the aquifer, it may be possible to meet ground-water cleanup targets at the compliance point in the short term. DNAPL mass removal will always lead to faster attainment of ground-water cleanup goals in the long term, as compared to the condition in which no source removal action is taken.

8.1.2.5 Clean Air Act (CAA)

The CAA and the 1990 amendments establish primary and secondary ambient air quality standards for protection of public health, as well as emission limitations for certain hazardous pollutants. Permitting requirements under CAA are administered by each state as part of State Implementation Plans (SIP) developed to bring each state in compliance with National Ambient Air Quality Standards (NAAQS).

Pump-and-treat systems often generate air emissions (when an air stripper is used). Source removal technologies that use thermal energy (e.g., steam injection or resistive heating) also may have the potential to generate air emissions, unless adequate controls are implemented. Surface emission tests conducted in the resistive heating plot during and after the demonstration showed TCE emissions that were noticeably above background levels. This indicates that the vapor recovery system needs to be designed for better capture. This is an issue of concern for this technology.

8.1.2.6 Occupational Safety and Health Administration (OSHA)

CERCLA remedial actions and RCRA corrective actions must be carried out in accordance with OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provide for the health and safety of workers at hazardous waste sites. On-site construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of RCRA, which provides safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, also must be met.

The health and safety aspects of resistive heating are addressed in Section 3.2.3, which describes the operation of this technology at Launch Complex 34. Level D personal protective equipment generally is sufficient during implementation. Operation of heavy equipment, handling of hot fluids, and high voltage are the main working hazards and are dealt with by using appropriate PPE and trained workers. Monitoring wells should be fitted with pressure gauges and pressure release valves to facilitate sampling during and/or after the resistive heating application. All operating and sampling personnel are required to have completed the 40-hour HAZWOPER training course and 8-hour refresher courses. There were no injuries during the resistive heating demonstration at Launch Complex 34.

8.1.3 Long-Term Effectiveness and Permanence

The resistive heating treatment leads to removal of DNAPL mass and therefore permanent removal of contamination from the aquifer. Although dissolved solvent concentrations may rebound in the short term when ground-water flow redistributes through the treated source zone containing DNAPL remnants, in the long term, depletion of the weakened source through dissolution will continue and lead to eventual and earlier compliance with ground-water cleanup goals.

8.1.4 Reduction of Toxicity, Mobility, or Volume through Treatment

Resistive heating affects treatment by reducing the volume of the contamination and possibly, reducing its toxicity as well (depending on how much the degradation pathway contributes to contaminant mass removal).

8.1.5 Short-Term Effectiveness

Short-term effectiveness of the resistive heating technology depends on a number of factors. If the short-term goal is to remove as much DNAPL mass as possible, this goal is likely to be met. If the short-term goal is to reduce dissolved contaminant levels in the source zone, achievement of this goal will depend on the hydrogeology and DNAPL distribution in the treated region. As seen in Section 5.2.1, TCE levels declined sharply in the monitoring wells in the resistive heating plot, but were well above federal or state MCLs. Geologic heterogeneities, preferential flowpaths taken by the oxidant, and localized permeability changes that determine flow in the treated region may lead to such variability in post-treatment ground-water levels of contamination. As discussed in Section 8.1.2.4, the chances of DNAPL mass removal resulting in reduced contaminant levels at a compliance point downgradient from the source is more likely in the short or intermediate term. In the long term, DNAPL mass removal will always shorten the time required to bring the entire affected aquifer in compliance with applicable standards.

8.1.6 Implementability

As mentioned in Section 7.2, site preparation and access requirements for implementing the resistive heating technology are minimal. Firm ground for setup of the heating equipment (such as electrodes, transformer, cables, etc.) is required. The equipment involved are commercially available, although the electrical transformer and power supply required are relatively large, and may require time to acquire. Setup and shakedown times are relatively high compared to other technologies, such as chemical oxidation. Overhead space available at open sites generally is sufficient for housing the resistive heating equipment. Accessibility to the targeted portion of the contamination under the Engineering Support Building at Launch Complex 34 was relatively good with electrodes inserted from the outside. However, electrodes installed from inside the building may be required to remediate more of the contamination under the building. This may disrupt the use of the building for the period of the treatment. The vendor suggests that electrodes inside the building can be flush-mounted, allowing continued use of the building. In this case, the installation cost would be higher.

8.1.7 Cost

As described in Section 7.4, the cost of the resistive heating treatment technology, implemented at Launch Complex 34, is competitive with the life-cycle cost of pump and treat (over a 30-year period of comparison). The cost comparison becomes even more favorable for source remediation in general when other tangible and intangible factors are taken into account. For example, a DNAPL source, such as the one at Launch Complex 34, is likely to persist much longer than 30 years (the normal evaluation time for long-term remedies), thus necessitating continued costs for pump and treat into the distant future (perhaps 100 years or more). Annual O&M costs also do not take into account the nonroutine maintenance costs associated with the large amount of downtime typically experienced by site owners with pump-and-treat systems.

Factors that may increase the cost of the resistive heating technology are:

- Operating requirements associated with any contamination further under a building, where angled electrodes are not sufficient and the aquifer has to be accessed from inside the building.
- Need for additional vapor or hydraulic control (e.g., with extraction wells) and any associated need to treat and dispose/reinject extracted fluids. This may be required to ensure that TCE vapors reach the vadose zone, where they can be captured, and are not obstructed by aquifer heterogeneities (such as the Middle Fine-Grained Unit).
- Regions with high unit cost of power.

8.1.8 State Acceptance

The ITRC, a consortium of several states in the United States, is participating in the IDC demonstration through review of reports and attendance at key meetings. The ITRC plays a key role in innovative technology transfer by helping disseminate performance information and regulatory guidance to the states.

The IDC set up a partnering team consisting of representatives from NASA and Patrick Air Force Base (site owners), U.S. EPA, State of Florida Department of Environmental Protection (FDEP), and other stakeholders early on when the demonstration was being planned. The partnering team was and is being used as the mechanism to proactively obtain regulatory input in the design and implementation of the remediation/demonstration activities at Launch Complex 34. Because of the technical limitations and costs of conventional approaches to DNAPL remediation, state environmental agencies have shown growing acceptance of innovative technologies.

8.1.9 Community Acceptance

The resistive heating technology's low noise levels and ability to reduce short- and long-term risks posed by DNAPL contamination are expected to promote local community acceptance. Supply of sufficient power and control of air emissions may be issues of concern for communities.

8.2 Operability

Unlike a pump-and-treat system that may involve continuous long-term operation by trained operators for the next 30 or 100 years, a source remediation technology is a short-term application. The field application of the resistive heating treatment demonstration in the 75-ft × 50-ft plot at Launch Complex 34 took about 11 months to complete. The remediation generally is done as a turnkey project by multiple vendors, who will design, build, and operate the resistive heating system. Site characterization, site preparation (utilities, etc.), monitoring, and any waste disposal often are done by the site owner. The resistive heating process is patented, but is commercially available from multiple licensed vendors.

The resistive heating treatment is relatively complex and requires proficient operators trained in this particular technology. Handing of hot fluids and high-voltage electrical equipment may require additional precautions.

8.3 Applicable Wastes

Resistive heating has been applied to remediation of aquifers contaminated with chlorinated solvents, polycyclic aromatic hydrocarbons (PAHs), and petroleum hydrocarbons both in the vadose and saturated zones. Source zones consisting of perchloroethylene (PCE) and TCE in DNAPL or dissolved form, as well as dissolved *cis*-1,2-DCE and vinyl chloride can be addressed by resistive heating.

8.4 Key Features

The following are some of the key features of resistive heating that make it attractive for DNAPL source zone treatment:

- In situ application
- Aboveground use of the site can continue during application
- Uses relatively complex, but commercially available, equipment
- Relatively fast field application time possible, when applied properly
- The heat generated distributes well in the aquifer in both high-permeability and low-permeability zones, thus achieving better contact with contaminants
- At many sites, a one-time application has the potential to reduce a DNAPL source to the point where either natural attenuation is sufficient to address a weakened plume, or pump and treat could be applied for a shorter duration in the future.

8.5 Availability/Transportability

Resistive heating is commercially available from multiple vendors as a service on a contract basis. All reusable system components can be trailer-mounted for transportation from site to site. Electrodes and other subsurface components usually are left in the ground after resistive heating application.

8.6 Materials Handling Requirements

Resistive heating technology requires hot fluids handling capabilities. Heavy equipment needs to be moved around with forklifts. Drilling equipment is required to install subsurface electrodes. Design and operation of the high-voltage electrical equipment requires specially trained operators.

8.7 Ranges of Suitable Site Characteristics

The following factors should be considered when determining the suitability of a site for the resistive heating treament:

- **Type of contaminants.** Contaminants should be amenable to mobilization, volatilization, or degradation by heat.
- **Site geology.** Resistive heating treatment can heat sandy soils, as well as silts or clays. However, aquifer heterogeneities and preferential flowpaths can make capturing the contaminants in the extraction system more difficult. DNAPL source zones in fractured bedrock also may pose a challenge. Longer application times and higher cost may be involved at sites with a high ground-water flow velocity because of increased rate of heat loss from the treated zone.
- **Soil characteristics.** Both low- and high-permeability soils can be heated by resistive heating treatment.
- **Regulatory acceptance.** Regulatory acceptance is important for this application. Improvements in vapor transport and recovery are necessary to increase acceptance.
- **Site accessibility.** Sites that have no aboveground structures and fewer utilities are easier to remediate with this technology. Presence of buildings or a network of utilities can make the application more difficult.

None of the factors mentioned above necessarily eliminates the resistive heating technology from consideration. Rather, these are factors that may make the application less or more economical.

8.8 Limitations

The resistive heating technology has the following limitations:

- Not all types of contaminants are amenable to heat treatment. In addition, some cocontaminants, such as certain heavy metals, if present, could be mobilized by heating.
- Aquifer heterogeneities can make the application more difficult, necessitating more complex application schemes, greater amounts of heat (or electricity), and/or longer application times. The limitation

lies not so much with the ability of the resistive heating technology to heat the subsurface, but with its ability to transport and capture the contaminant vapors in an efficient manner.

- Some sites may require greater hydraulic control to minimize the spread of contaminants. This may necessitate the use of extraction wells and any associated aboveground treatment.

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